



ANALYSIS OF DESERT SHRUBS ALONG FIRST-ORDER CHANNELS ON DESERT PIEDMONTS: POSSIBLE INDICATORS OF ECOSYSTEM CONDITION AND HISTORIC VARIATION

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1.0 EXECUTIVE SUMMARY

The overall goal of this project was to investigate whether specific shrub and tree species distributed along the first-order channels draining desert piedmonts can provide efficient and reliable signals of environmental change (resulting from either natural disturbance or military activities) and ecological condition. Specific project objectives sought to:

1. Determine the historic range in variation of selected desert vegetation common to alluvial fan surfaces and first-order channels
2. Evaluate changes in soil and surface hydrology (due to either military activities or natural environmental variation), which can be shown to predominately account for changes in ecosystem condition, especially the historic contraction of vegetation along the margins of alluvial fan surfaces
3. Provide recommendations to further develop and test procedures that can be used to monitor ecosystem status, and to identify impacts related to natural disturbance versus military activities.

Six first-order basins were studied ranging in size from approximately 10,000–48,000 m². These basins had a nearly continuous cover of desert pavement prior to any disturbance. Natural and impacted basins were paired geographically to ensure similar soil and climatic conditions. The soil and surface cover of these basins, as well as the limitation of vegetation to drainage channels, is representative of landsurface conditions in arid and hyperarid regions of the southwest and the world.

Soil and geomorphic measurements and analysis provided insights into the spatial distribution of soil moisture and the soil properties that impact soil water and vegetation. Methods and standard laboratory investigations data were provided by Soil Survey Staff on the volume of surface runoff per precipitation event, and the extent of the hydrologic connection between surface anomalies and surface drainage.

Soil studies revealed considerable differences in soil characteristics, water conductivity, and soluble salt content in soils underlying desert pavements compared to soil underlying channel surfaces. High salt content can complicate data interpretation, but land managers can use surface measurements of bulk soil electrical conductivity to measure soil moisture and possible anthropogenic effects over large areas as long as supplemental data is available for comparison.

Biologic characterizations included study of species common to this area: creosotebush, ironwood, and blue paloverde. Analysis of these species indicated that climatic variation and alteration of surface-contributing source areas control the flow of surface water and are the primary elements affecting ecological condition.

Incorporation of some of the strategies and techniques for soil and hydrologic characterization as outlined in this report would be beneficial to conservation managers and their agencies. In conjunction with consultation with geotechnical advisors, we suggest the integration of vegetation dynamics and soil-landscape relations to assessments of ecological condition.

The results as outlined in this report confirm that vegetation along first- and higher-order channels provide an efficient means of examining ecosystem condition in arid environments. Additional sampling strategies should include a survey of plant-water use across a range of drainage types, observation of leaf pubescence as a determinant of plant health in relation to hydrology, additional stable isotope analyses, incorporation of new time-domain reflectometry (TDR) technology in the testing of soil moisture, further analysis of precipitation patterns in extensively disturbed desert pavements, and additional numerical modeling.

2.0 Background

2.1 INTRODUCTION

Approximately seventy percent of Department of Defense (DoD) lands constitute arid and semiarid environments within the United States. The majority of this land that is suitable for wheeled or track vehicles consists of desert piedmont plains (bajadas) that are largely comprised of alluvial fans covered with desert (rock) pavement and active washes (Fig. 2.1.1). The greatest concentration of biomass and biodiversity occurs along low-order channels that drain alluvial fans and other piedmont areas and along prominent washes marginal to alluvial fans. This distribution of vegetation is primarily due to a considerable increase in plant-available water that is derived from ephemeral precipitation runoff from surrounding soils, desert pavements, and rocky highlands. In some cases, this augmented water may be two or three times the amount of water relative to the amount received from precipitation alone. Any change in runoff-supplied water, whether due to military activities (i.e., disruption of soil and pavements) or natural environmental change (i.e., climatic variation), will directly impact the ecosystem.



Figure 2.1.1. Oblique aerial view of a typical desert piedmont in the lower Colorado River region of the Sonoran Desert. Nearly all of the biomass and biodiversity are located along ephemeral washes that are marginal to areas of soils covered with desert pavement.

Observations of the land surfaces and ecosystems common to arid regions across the desert southwestern U.S. suggests that changes are occurring. At the Yuma Proving Ground (YPG) in southwestern Arizona, vegetation density noticeably decreases downstream of piedmont areas heavily impacted by military activities (training, testing, infrastructure). Field observations of current soil and vegetation patterns in areas not impacted by military activity, however, strongly indicate that a natural contraction of vegetation along alluvial fan surfaces and first-order rills may be occurring and that this change is not directly related to military land use. Changes in desert vegetation, therefore, are likely due to natural and anthropogenic forces. Recognition of physical and biological signals indicating change in the flux and availability of water due to either military, anthropogenic, or

environmental causes will greatly benefit conservation management of sensitive desert lands, and will contribute to the development of cost-effective, scientifically sound land-management strategies.

2.2 PROJECT HYPOTHESIS

We hypothesized that the status of *vegetation along first-order channels will provide a readily observable signal of ecosystem change*. The scientific basis for this hypothesis is that predictable relations exist among landscape position, soil features that control the spatial and temporal distribution of soil moisture, and vegetation condition (McAuliffe, 1994; McAuliffe and McDonald 1995; Hamerlynck et al., 2002). Much of the ephemeral water available for desert ecology appears to be derived from episodic surface runoff from alluvial surfaces; therefore, any change in surface runoff will directly correspond to changes in vegetation vitality along active washes. Vegetation along first-order drainages is likely to be impacted first by any natural or anthropogenic changes in the flux of surface runoff because these drainages are directly linked to surface runoff. Higher-order channels may not be as sensitive to environmental change because as channel order increases, runoff is supplied by an increasingly larger contributing area and greater number of contributing channels. This, in turn, will result in a greater frequency of run-off supplied water to higher-order channels and associated vegetation. In other words, an increase in the likelihood of ephemeral runoff may result in a decrease in vegetation sensitivity to environmental change due to a greater availability of water. If this hypothesis is true, then monitoring the ecology of selected first-order channels across both impacted and non-impacted drainage basins may provide an environmental “heads-up” about potential impacts to downstream ecosystems and related changes in the water supply from upland areas.

2.3 PROJECT OBJECTIVES

The focus of this project was to determine if important shrub and tree species distributed along first-order channels draining desert piedmonts can provide efficient and reliable signals of environmental change and desert ecological condition resulting from either natural disturbance or military activities. This project focused on three main objectives:

1. Determine the historic range in variation of desert vegetation common to alluvial fan surfaces and first-order rills.
2. Evaluate if changes in soil and surface hydrology, due to either military activities or natural environmental variation, can be shown to be the primary causes of changes in ecosystem condition, especially the historic contraction of vegetation along the margins of alluvial fan surfaces.
3. Provide recommendations that can be used to further develop and test procedures that can be used to monitor ecosystem status and to identify impacts related to natural disturbance relative to military activities.

Our interdisciplinary approach to meet these objectives combined historic background mortality of plants, ecophysiological measurements of living plants that are marginal to areas of plant mortality and the development of the basic soil-hydrological foundation connecting zones of mortality and living plants.

2.4 REPORT FORMAT

Project accomplishments are discussed in three main sections that follow this introduction. The first section demonstrates field observations about both natural and anthropogenic-related changes to desert vegetation at YPG. The purpose of this section is to better illustrate the type of ecosystem problem facing land resource managers in the arid regions of the desert Southwest. The second section focuses on how soil, hydrologic, and vegetation processes are connected across the desert piedmont. This section presents key landscape, climate, and plant-response characterization data. The purpose of this section is to show that integration across geomorphic and biologic disciplines is required to adequately understand and manage desert ecosystems. The third section provides a more detailed examination of vegetation dynamics through a focus on plant performance. This section incorporates ecophysiological data, including plant-water potential, isotopic analysis, and field measurements of plant canopy volume to demonstrate how the vegetation responds to landscape control of plant-available water. The purpose of this section is to show how the dynamics of desert plants are directly linked to landscape position and environmental variables. Conclusions, a transition plan, and recommendations for future work follow and complete the report.

2.5 ENVIRONMENTAL SETTING

The study area lies within the northwest corner of the YPG and is approximately 20 km south of Blythe, California (Fig. 2.5.1). The YPG is a general-purpose testing facility within the U.S. Army Test and Evaluation Command. Yuma Proving Ground is located along the Colorado River in southwestern Arizona, and is within the Lower Colorado River subdivision of the Sonoran Desert. Elevation across YPG ranges from 56 to 823 m above msl. Yuma Proving Ground covers 3367 km², with nearly 70 percent consisting of broad desert piedmonts with an extensive cover of Holocene and Pleistocene alluvial fans and ephemeral washes. Most of the alluvial fan soil surface is covered with a desert pavement.

The piedmont area investigated in this report is located along alluvial fan-terraces north of Gould Wash, a large ephemeral wash that flows west from the Chocolate Mountains and into the Colorado River. Elevation of the study site is about 200 m above msl.

Climate

The average annual temperature across YPG is 23°C. Annual precipitation is 91 mm and largely occurs in the winter months from frontal storms and during late summer months from convective storms and infrequent tropical cyclones. The tropical storm influence can occur during the active phase (rare), during decay stages (occasional), or by way of remnant moisture plumes from a distant demise (common). These causes are, in turn, modulated by larger-scale, oceanic climate phenomena, primarily oriented in the Pacific. Among these sources of variability are El Niño and La Niña (collectively, ENSO) and perhaps the Pacific Decadal Oscillation (PDO), centered in the northern Pacific Ocean. There also appear to be trends in recent years associated with global climate change, or with other unknown sources of global climate variability. The region has experienced the wettest period in its historical record over the past two to three decades. But in the past few years the area has been much drier, possibly a more common occurrence with the apparent recent phase change of the PDO.

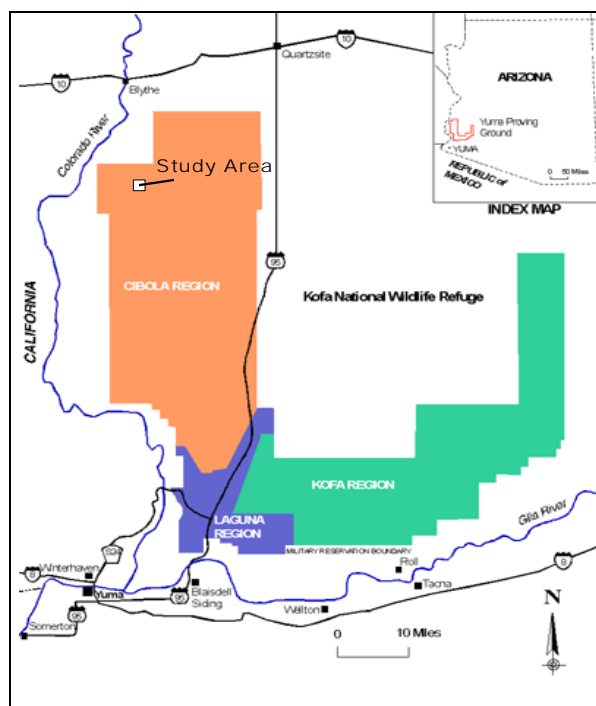


Figure 2.5.1. General location map of the YPG, which covers an extensive area in southwestern Arizona. The study site for this project is located along a piedmont that borders the Colorado River.

As in other arid environments, precipitation variability on the YPG is high on all time scales. Annual precipitation has a coefficient of variation of about 0.44, and multi-station combinations (climate divisions) have varied from about 21 to 275% of average during individual years over the past century. Ten-year averages have fluctuated by about 30%, and thirty-year means have varied from 82 to 111% of the long-term (106 year) average. At the Yuma airport, precipitation is received, on average, during only 17 days per year, or 51 hours per year of measurable rain (at least 0.25 mm). Thus, rain occurs on 0.58% of the hours. In December and January, rain occurs on about 1.2% of the hours; and in the peak month of August during the monsoon, rain occurs on 0.72% of the hours, more than twice as often as in July, and much more than in June. June has the least frequent rainfall with only nine total hours of precipitation occurring from 1961 to 1990, or 0.04% of the hours. Any precipitation that does fall, however, tends to be intense, averaging 1.45 mm per rainy hour on an annual basis, and 2.93 mm per rainy hour in July and August. This intensity exceeds, by a considerable amount, humid locations such as Portland, Oregon. The wettest day of the year brings about 32% of the annual precipitation, and the wettest hour of the year typically brings about 12% of the annual precipitation.

Geomorphic Setting

The extensive areas of desert piedmonts (bajadas) at YPG have a nearly ubiquitous cover of well-developed desert (rock) pavements that have formed on early Holocene to Pleistocene alluvial

deposits (Fig. 2.5.2). Pavements consist of a single layer of surface stones that generally range in size from 1 to 5 cm (Fig. 2.5.3), which form an armor of closely packed stones. The tops of most clasts have a well-developed layer of rock varnish (commonly referred to as “patina”) that forms the characteristic dark surface of these alluvial surfaces (Fig. 2.5.3a). Underlying the pavement is a gravel-poor and fine-textured vesicular (v) A horizon (Fig. 2.5.3b). The use of “v” for vesicular horizons does not follow current National Resource Conservation Service (NRCS) nomenclature for assigning soil master horizon subordinate properties (Soil Survey staff, 1998), but it is frequently used by scientists working with soils in the southwestern U.S. The Av horizon is essentially a layer of dust that has accumulated below the surface layer of stones (McFadden et al., 1987; 1998). Desert pavements are prominent features in arid and semiarid environments and can be found on a variety of landforms (Cooke and Warren, 1993; Bull, 1991). Desert pavements are common to all arid regions and can cover extensive areas of the bajada. These stone-covered soils are also commonly referred to as reg, hamada, gobi, and gibber plains.



Figure 2.5.2. Surface view of the extensive desert pavements at YPG. Much of the bajada surface is covered by a layer of stones at the soil surface.

The extensive alluvial fan surfaces have been widely incised by secondary drainages (rills and low-order washes) that form tributaries which discharge into the main channels originating from the surrounding mountain highlands (Fig. 2.5.2). Most of the channels are first order (i.e., the uppermost defined fluvial channel within an organized drainage network). The morphology of these channels varies from silt-covered depositional bars to gravel-covered channels deeply inset into the fan alluvium. First-order channel widths range from about 1 m in the upper reaches to about 4–6 m along the lower reaches.

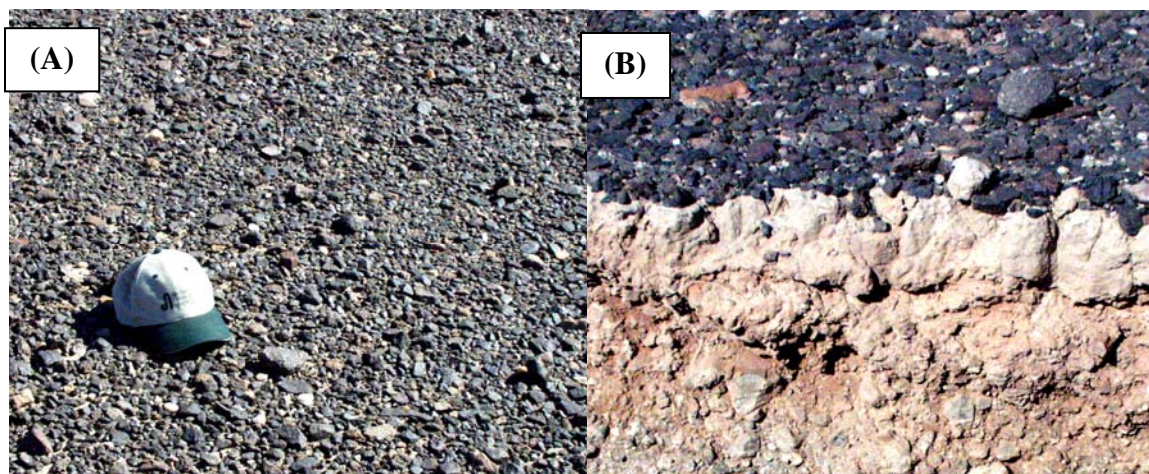


Figure 2.5.3. (A) Interlocking character of stones that form the desert pavement. (B) Cross-section view of desert pavement comprised of a single layer of stones, the gravel-poor and fine-textured Av horizon, and the underlying subsoil.

Vegetation-Description and Justification for Species Studied

The pavement-covered soils are largely devoid of vegetation. Vegetation along channels mainly consists of *Larrea tridentata* (creosotebush), *Ambrosia dumosa* (white bursage), *Pleuraphis rigida* (big galleta grass), *Fouquieria splendens* (ocotillo), *Carnegiea gigantea* (saguaro), *Olneya tesota* (ironwood), *Cercidium floridum* (blue paloverde), and *Cercidium microphyllum* (foothill paloverde) (Fig. 2.5.4). Most of the biomass along alluvial channels occurs as ironwood, paloverde and creosotebush.

Long-lived perennial desert plants display considerable diversity in growth and physiological strategies that optimize the trade-off between photosynthetic carbon gain and the associated cost of transpirational water use (Ehleringer, 1994; Smith et al., 1997). These diversities give us the opportunity to use plant ecophysiological characteristics to monitor environmental variation across a range of spatial and temporal scales. Desert ironwood and foothills paloverde are both deep-rooted members of the bean family (Fabaceae). Both these species are considered to be evergreen and are frequently classified as phreatophytic (partially or completely reliant on saturated-zone ground water), but they do grow in upland locations where ground-water depth is either highly variable or unreachable. In such locations, both show a marked reduction in growth and likely rely more on deep and fairly persistent soil water that is recharged from run-on events (Szarek and Woodhouse, 1977, 1978; Smith et al., 1997).

Ironwood produces a main bole of highly durable heartwood and supports a persistent canopy of leaves capable of year-round physiological activity that is the sole carbon-fixing portion of the plant (Szarek and Woodhouse, 1977; Smith et al., 1997). In contrast, paloverde has soft, porous wood and is covered with green bark that is photosynthetically competent and contributes over 70% of annual carbon gain (Szarek and Woodhouse, 1978). Paloverde also produces an ephemeral leaf canopy shortly after sufficiently heavy rains. These two photosynthetic components (of stem and ephemeral leaves) are very different. Stem photosynthesis is under much greater diffusive limitation and displays greater water use efficiency (WUE: CO₂ gain/H₂O loss) compared to ephemeral leaves.

Thus, stem photosynthesis represents allocation for long-term hardiness, while leaves represent opportunistic allocation (Comstock and Ehleringer, 1990).

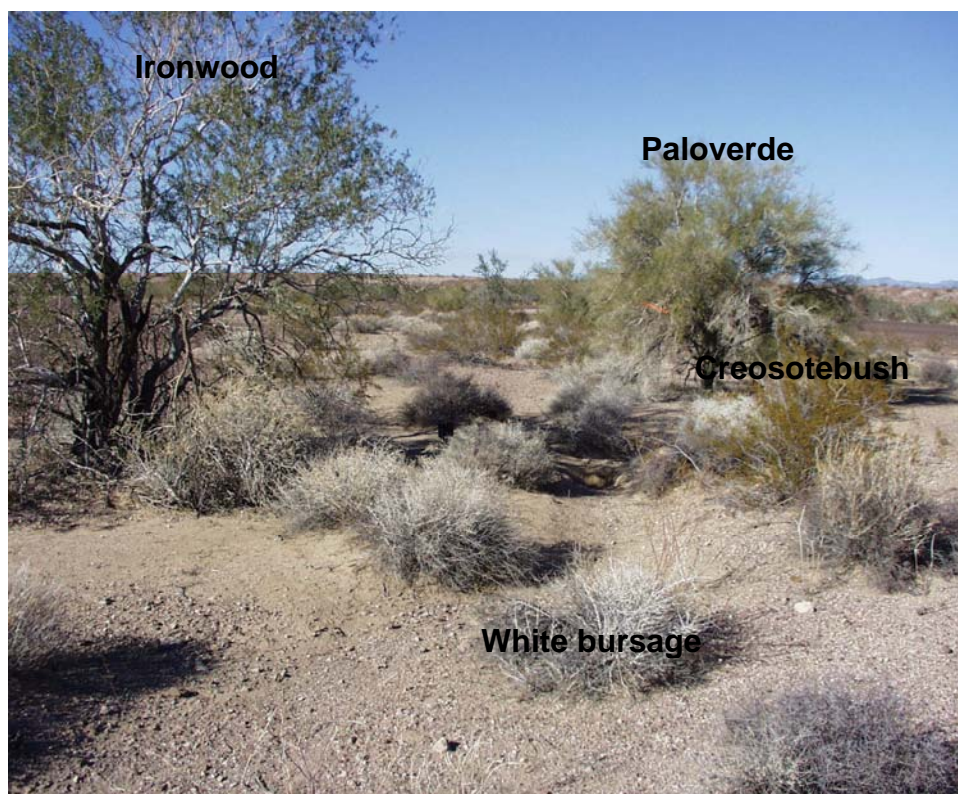


Figure 2.5.4. View of dominant vegetation along first-order channels. Ironwood and paloverde are the dominant trees species across YPG and much of the lower Sonoran Desert. Creosotebush is the dominant shrub across the Sonoran and Mojave Deserts.

The third plant selected, creosotebush is a medium-to-large shrub and is the dominant plant of North American warm deserts (Smith et al., 1997; Whitford, 2002). Creosotebush has highly drought- and temperature-tolerant evergreen leaves that persist over several years (Oechel et al., 1972; Seemann et al., 1986; Hamerlynck et al., 2000). Creosotebush is less deeply rooted than ironwood and paloverde, and its seasonal water relations reflect soil-water dynamics in the upper 1–2 m of soil (McDonald et al., 1996; Hamerlynck et al., 2000, 2001). Thus, creosotebush should respond most strongly to wetting and dry-down conditions compared to ironwood and paloverde.

The use of these contrasting and co-existing plants provides a suite of ecologically-based response variables that are useful for characterization of the critical features underlying variation in soil hydrology in this desert system. Growth in all three species should reflect fundamental aspects of deep and shallow soil hydrology. In addition, the hard wood of ironwood provides a persistent record of plant mortality, which should be related to critical variation in soil hydrology, while the deep rooting habit and persistent canopy can be used to track variation in ecophysiological performance in response to deep soil-water dynamics. Differences in stem and leaf photosynthesis in paloverde

provide an additional degree of resolution, with stem performance more tightly coupled to deep soil water, and ephemeral leaves more likely tied to shallower soil-water dynamics.

3.0 Technical Approach

We integrated the analyses of soil, geomorphic, hydrologic, and biologic processes to test the hypothesis that the distribution of desert shrubs along first-order channels can be used as an indicator of overall ecological condition. The project design consisted of three interrelated components (each address the three project objectives):

- (1) Evaluation of the historic range of plant variability
- (2) Characterization of the correlation between soils and plant available water
- (3) Evaluation of the ecophysiological response of key desert plants along first-order drainages.

We determined the historic range of vegetation through field observations of the distribution of signs of plant mortality along alluvial channels, and across the broad areas of piedmont surface within the study area.

Evaluation of the relations between soils and vegetation, and related ecophysiological response were correlated through characterization of soil-hydrologic-plant linkages among six first-order drainage basins that range in size from about 10,000–48,000 m² (Fig. 3.0.1; Table 3.0.1). The six drainages are located across two extensive alluvial terraces. The upper three drainages (hereafter, north drainages) are labeled N1, N2, and N3; the lower three drainages (hereafter, south drainages) are labeled S1, S2, and S3.

We separated each of the six study drainages into two plots (Fig. 3.0.2). One plot was located along the uppermost reach of the first-order drainage (hereafter referred to as the upper channel) that has ironwood and paloverde trees. A second plot was located along the lowermost extent of the first-order channel (hereafter referred to as the lower channel) where trees lay just up-gradient from the distal end of the first-order channel. Vegetation consisting of ironwood, paloverde, and creosotebush was assessed at two plots within each of the six drainages. In two of the drainages, N1 and S3, soil properties were characterized and soil moisture was measured.

Summary of Methods Used

Methods used are described in detail for each section that presents results and discussion for each of the three components. A summary of basic methods used is provided here and is listed according to each of the primary tasks listed in the project proposal.

Biological Characterization (Task 1)

Field observations and measurements were conducted on three important shrub and tree species: ironwood, paloverde and creosotebush. The sampled species—which differ in longevity, stress tolerance, and rooting habit—have distinct sensitivities to soil-water deficits, and thereby provide an

ideal basis for assessing alterations to soil hydrology and related environmental conditions. Plant physiological measurements included: 1) predawn and midday xylem water potentials, 2) midday net photosynthesis, stomatal conductance, and transpiration, and 3) stable carbon isotope ratio (δC^{13}) and tissue N and C.

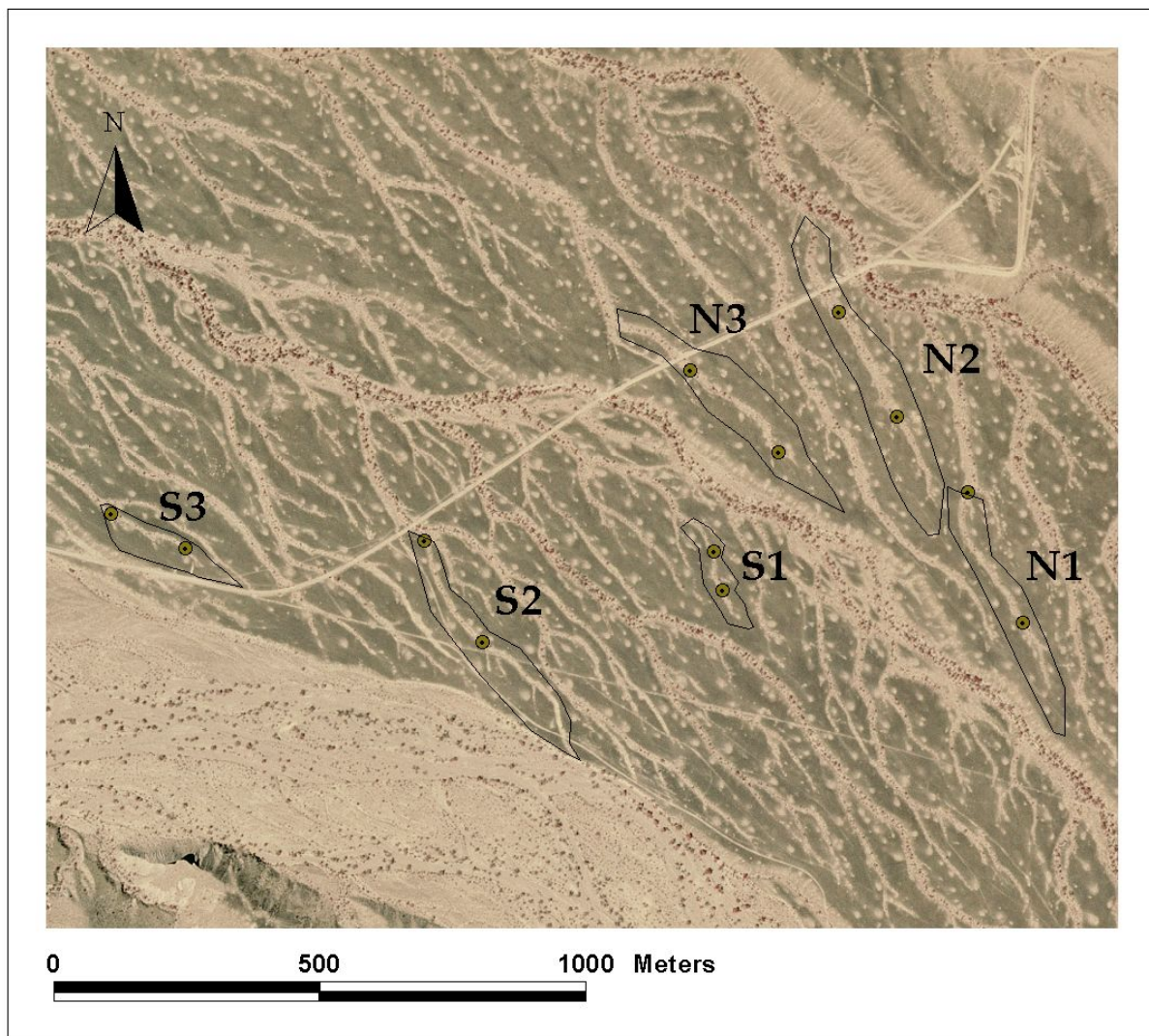


Figure 3.0.1. Layout of the six first-order drainages used in this study. Lines denote approximate boundaries of the drainages. Green circles mark locations of sampled vegetation. Areas of dark coloration are desert pavements, light colored and wavy lines are the channels, and light-colored dots are the plant scars. Cibola Lake Road crosses the field of view from southwest to northeast.

Soil and Geomorphic Characterization (Task 2)

Soil properties were characterized to develop an integrated foundation for spatial distribution of measured soil moisture and to evaluate soil properties that impact soil water and vegetation. Detailed soil descriptions were conducted at the several locations across the study site with an emphasis on

horizontal and vertical variation in properties that influence soil water balance. Laboratory analysis of sampled soils included: soil texture, bulk density, electrical conductivity, and pH. Field runoff plots were established to determine the relationship between precipitation and surface runoff. Field measurements were also conducted to determine surface infiltration.

Monitoring Soil Moisture (Task 3)

Measurements of volumetric soil moisture and temperature were collected using buried time-domain reflectometry (TDR) waveguides. A ground conductivity meter was used as a non-invasive method for determining the spatial variability of soil moisture and salinity. Field observations were also performed along first-order channels to determine periods of extent of channel flow and related changes in soil moisture.

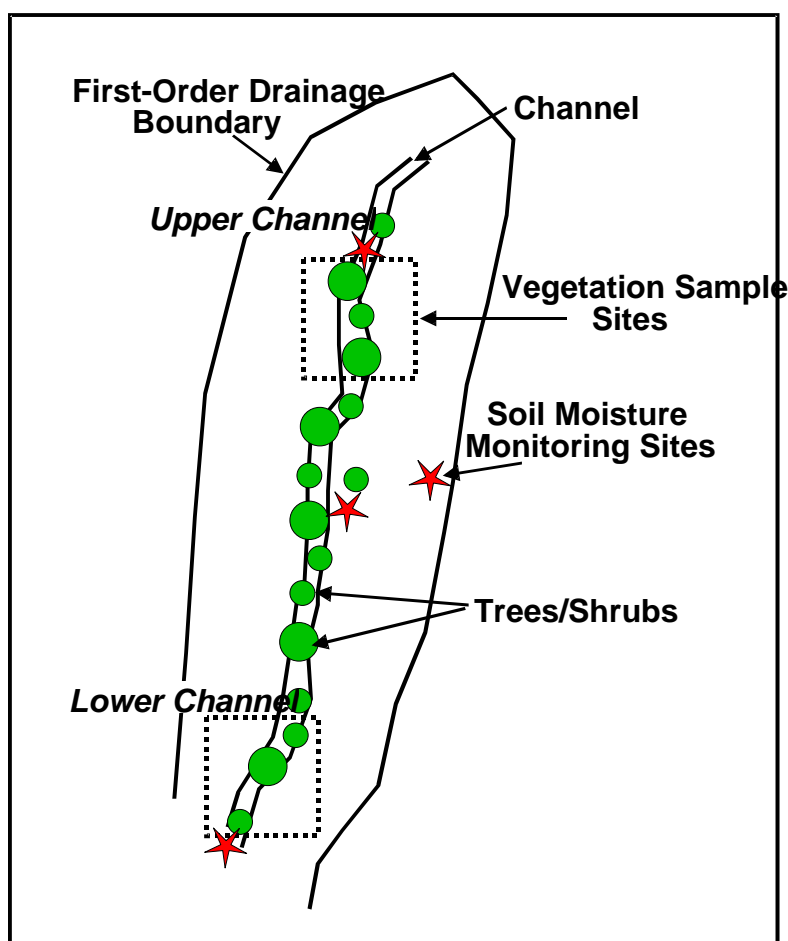


Figure 3.0.2. Schematic diagram showing experimental layout for the six first-order drainages in this study. Site consisted of two vegetation sampling plots (dotted box) with one in the upper channel and one in the lower channel, and four soil-moisture monitoring sites (red stars).

4.0 Project Accomplishments

4.1 HISTORIC AND PRE-HISTORIC CHANGES IN VEGETATION ALONG CHANNELS

A major challenge facing desert land-resource managers is how to distinguish changes in ecological condition due to short- and long-term variations in climate, and related natural changes in environmental factors, from those directly related to military or other anthropogenic activities. Although several environmental factors outside of direct military activities may impact ecological condition (e.g., invasive species, regional air quality), consideration of natural changes in climate, or more specifically, environmental factors controlling the flux of plant-available water, is a logical starting point from which to examine historic and prehistoric changes in vegetation common to the desert piedmonts across YPG. Measuring plant-available water is an effective strategy because water is the most critical resource in desert settings (Smith et al., 1997). The role of changing climate and its affect on plant-available water must also be considered when evaluating ecosystem health. Abundant paleoclimatic records over millennia developed for the desert Southwest show that climatic variations are frequent and dramatic, even within the last few centuries (Cayan et al., 1999; Redmond et al., 2002). Equally dramatic changes in modern climate may occur in the near future if predictions of global warming and the resulting shifts in storm tracks and precipitation are accurate. Monitoring desert ecosystem health is further complicated by the fact that deserts are clearly susceptible to small changes in environmental conditions. For example, slight changes in surface albedo or the seasonal distribution of rainfall have been shown to be possible factors driving desertification and the loss of ecosystem resources (Williams and Balling, 1996).

One method to evaluate future environmental impacts on desert vegetation, whether natural or anthropogenic, is to examine changes in the ecosystem related to short- and long-term changes in plant mortality. Plant mortality is, in turn, related to possible changes in the supply of plant-available water. The first part of the section examines basic shifts in historic tree mortality along first-order washes in both disturbed and undisturbed areas of the desert piedmont. The second section evaluates possible indicators of historic to prehistoric changes in the distribution of widespread features we term “plant scars.” An additional goal of this section is to provide documentation of the types of changes in ecosystem condition that have occurred. This type of information when combined with studies of geomorphic characterization and current soil, hydrologic, and vegetation processes provides a powerful tool in which to monitor and evaluate any future alteration to desert piedmonts related to climatic variation.

METHODS

Distribution of Trees along First-Order Channels

The linear distance of ironwood and paloverde along first-order channel length was determined by first determining the location of live and dead trees and the upper and lower ends of the first-order channels using a global positioning system (GPS). We used a Ranger 200CE GPS (Tripod Data Systems [TDS], Corvallis, Oregon). The GPS provides an approximate location as determined to within ± 25 cm. The upper boundary of each first-order drainage basin was defined as the ridgeline nearest the upper end of the first-order channel. The lower end of the first-order channel is the location where the first-order channel connects with another first-order or higher-order channel. All distances were determined by measuring along the first-order channel using ArcView 3.3. The basal

diameter of live trees was measured at 15 cm above the soil surface. Measurements were conducted along twenty-eight first-order drainages (which included all six study sites, see Fig. 3.0.1 and Fig. 3.0.2), with ten measurements along the smaller drainages on the south end of the study area, and eighteen measurements along the larger drainages on the north end of the study area.

Spatial Analysis of Plant Scars

We examined plant scars in the field at several sites across YPG. Soil pits were excavated through plant scars at three locations in the study area. Soil morphology was described using standard Soil Survey Staff (1998) methods. The spatial distribution of plant scars was analyzed by measuring the distance from the center of each plant scar to the margin of the nearest first-order channel.

Measurements were made with *Image J*, a public domain image processing and analysis program from the National Institutes of Health [<http://rsb.info.nih.gov/ij/>]. Distance measurements for plant scars were also compared with the distribution of distances measured between random points and the nearest edge of a first-order channel. Random points, generated on an x-y coordinate system consisting of an array of 2071 x 1418 screen pixels, were also measured. Distances from randomly selected pixels and the margin of the nearest first-order channel were similarly measured using *Image J*. Random points that occurred outside the delimited study area or within the width of first-order channel or the roadway were not included.

RESULTS

Impact of Vegetation in First-Order Channels Due to Land Use

A pronounced decrease in vegetation occurs down gradient from areas where surface runoff and channel flow have been decreased due to land use. Although we did not collect field data on the distribution of live and dead vegetation along channels draining areas of military activities, multiple field observations clearly indicate the severity of this impact. The best examples of this impact can be seen where roads or trails have been constructed across first-order and higher channels, and thus have terminated or severely decreased ephemeral surface flow (Fig. 4.1.1a). High mortality of vegetation downstream of roads, especially the distribution of important tree species such as ironwood and paloverde, clearly demonstrates how a lack of surface channel flow will directly impact the ecology of desert washes (Fig. 4.1.1b). By comparison, there is a considerable increase in vegetation, especially invasive species, upstream of roadways (Fig. 4.1.1c). This increase is attributed to ponding of surface runoff and an increase in percolation of water into channel sediments.

Additional increases in tree mortality occur down gradient of extensive areas where the soil surface has been severely impacted due to testing activities that have removed much of the desert pavement cover and fine-grained soil in near-surface horizons (Fig. 4.1.2). The examples shown in Figure 4.1.2 are common across YPG and other areas of the desert Southwest where vegetation occurring along ephemeral channels has been impacted by decreases in the flux of surface water (Schlesinger, et al., 1989).

Modern Distribution of Live and Dead Trees

Initial field observations along first-order drainages suggested that there might be trends in the distribution of live and dead ironwood and paloverde along first-order channels. We hypothesized

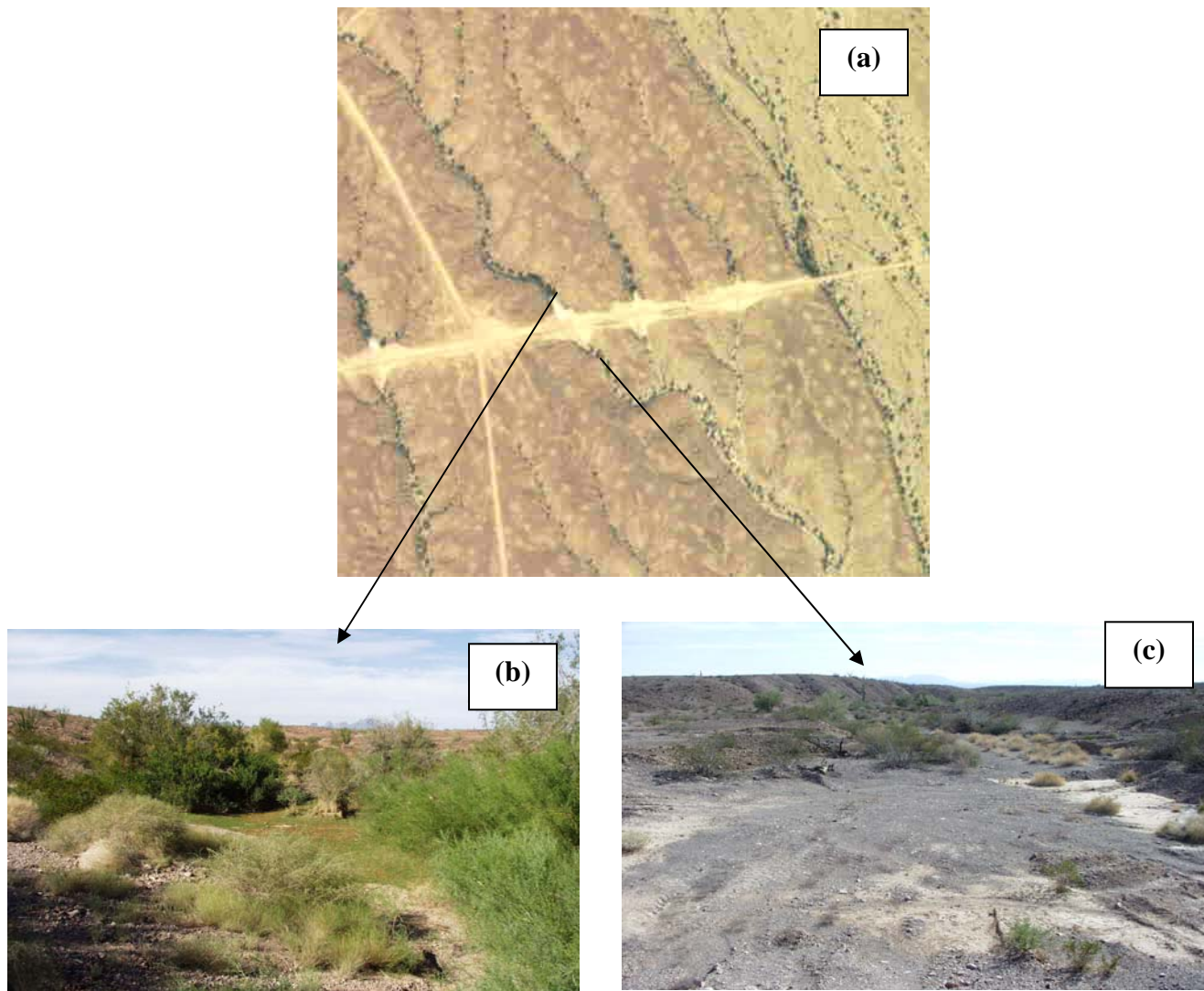


Figure 4.1.1. (A) Roads across drainages directly impact vegetation health. (B) Upstream side of drainage has abundant vegetation, but also many invasive species. (C) By comparison, downstream side of road has lost all major tree species and most shrubs. This pattern is common where roads block ephemeral channels.

that any trends in tree vitality, especially the spatial distribution of tree mortality, could provide information about recent environmental controls on tree dynamics, and that monitoring tree vitality may serve as a tool in monitoring ecosystem health.

Measured relations between basal tree diameter and distance down gradient along first-order channels supports a link between locations and tree response. Ironwood trees along the larger north drainages have significantly greater basal diameters than trees along the smaller south drainages (Fig. 4.1.3). Paloverde display similar trends, but the difference in tree diameters between north and south is not

as great. As mentioned above, the drainage basins on the north surface have larger surface areas relative to drainage basins than on the south surface (Table 3.0.2). Ironwood, therefore, has a good

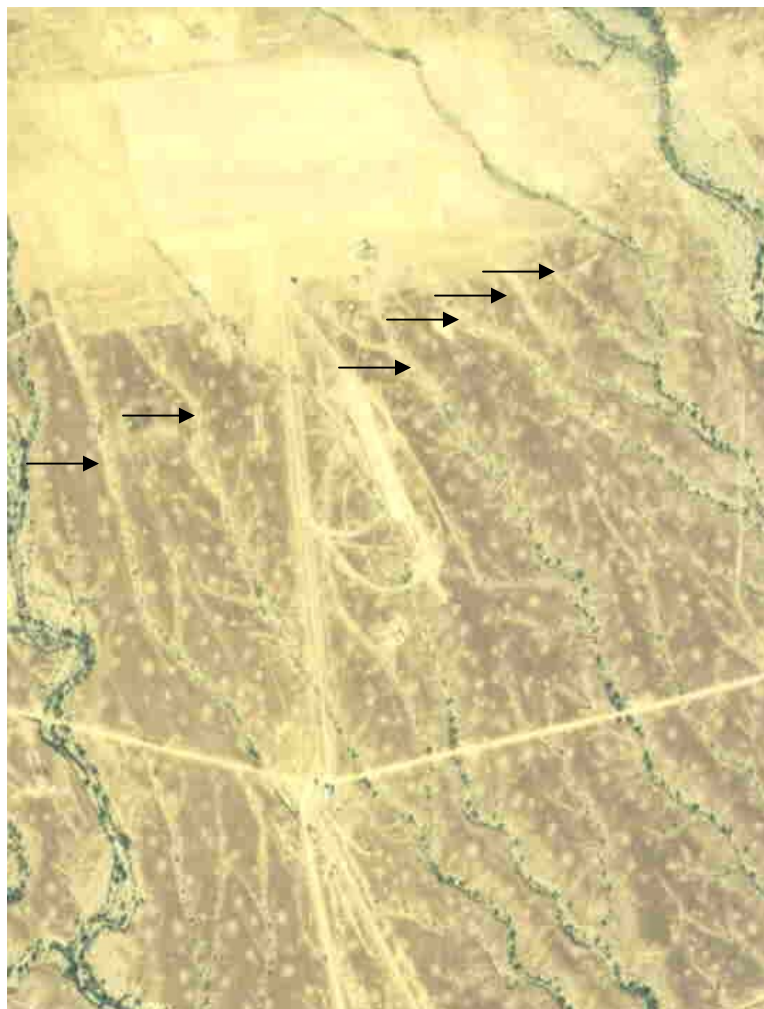


Figure 4.1.2. Vegetation downstream (arrows) of extensive areas of degradation of desert pavement and soils is diminished considerably due to loss of surface runoff.

linear relationship between basal diameter and distance to drainage head, especially for drainages on the north surface. By comparison, paloverde diameter does not show a strong relation between distance along the channel and basal diameter.

Apparent trends also occur in the spatial distribution of live and dead trees along first-order channels. The overall distribution of live ironwood is normally distributed and has a medium channel distance of about 158 m (Fig. 4.1.4). By comparison, the overall distribution of dead ironwood has a medium channel distance of 146 m but is noticeably skewed to shorter channel length. There is a pronounced increase in the frequency of dead trees at distances less than 140 m. Distance relations between live and dead trees vary between north and south drainages (Fig. 4.1.5). The mean channel distance to live ironwood is less than the mean channel distance to dead ironwood on north drainages. Slight

differences in the distribution between live and dead ironwood occur between the smaller south drainages and the larger north drainages. The distance along first-order channels to the location of

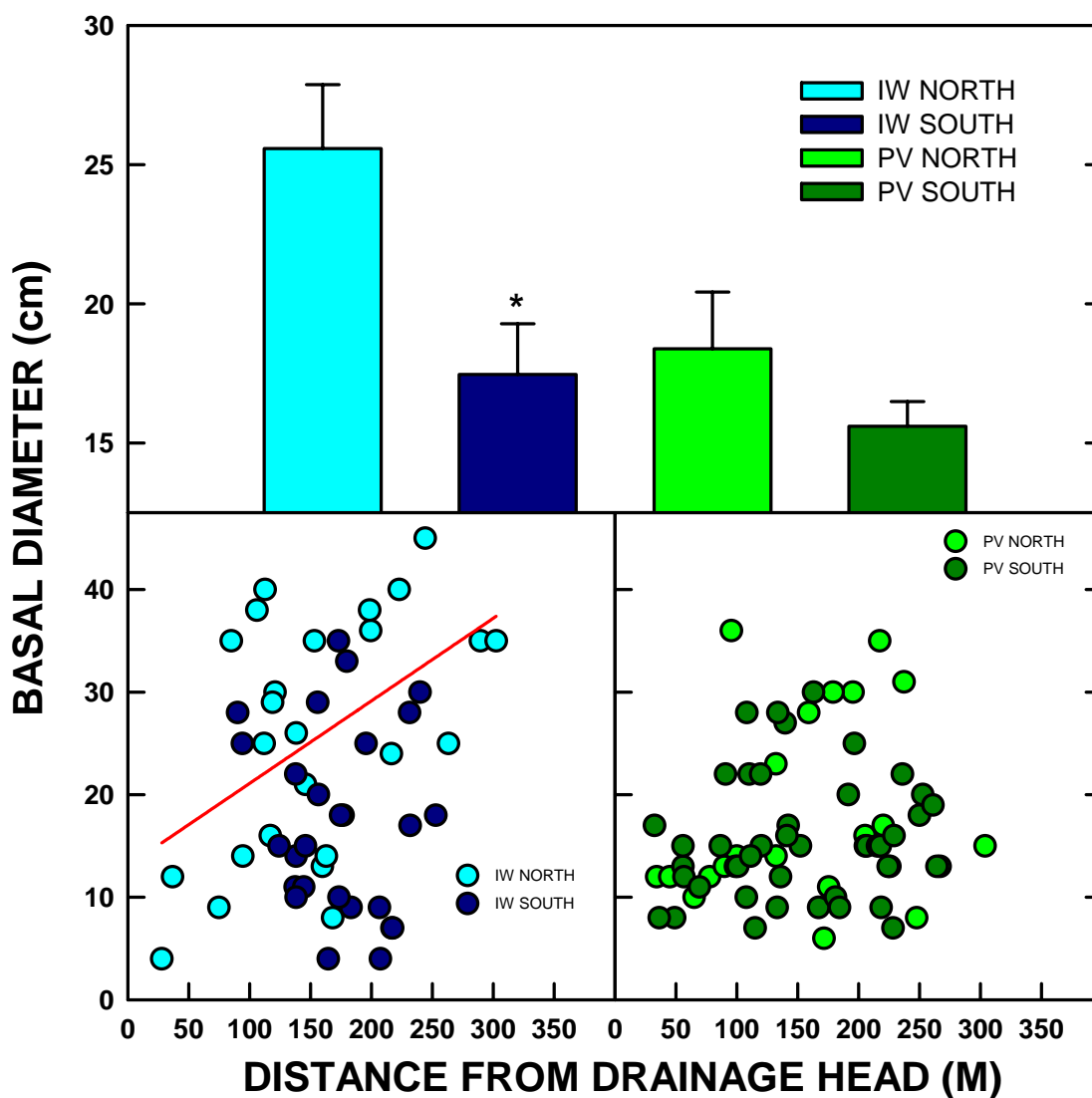


Figure 4.1.3. Relation between basal diameter and distance along first-order channel from top of drainage basin. Basal tree diameters are generally larger along the larger north drainages.

the first dead and live ironwood also indicates a possible correlation between distance along each channel and tree response (Fig. 4.1.5). There is a strong linear tie between the channel distance to live and dead trees on the south drainages, and a comparable scatter of points on the north drainages. This indicates that along the smaller south drainages, ironwood repeatedly establishes in the same channel location (i.e. new trees established along same channel location as dead trees). In contrast, the establishment of ironwood is likely anywhere along the channel of the larger north drainages.

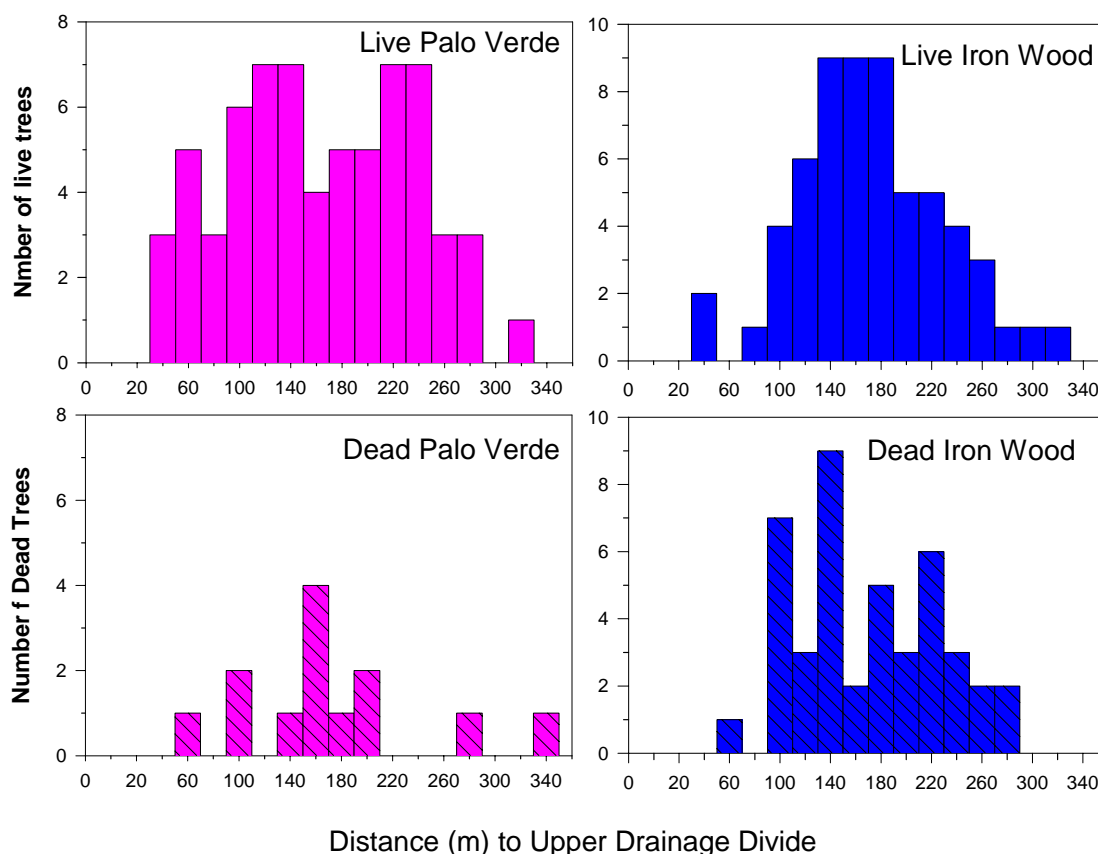


Figure 4.1.4. Histogram of frequency of live and dead trees as a function of distance downstream along first-order channels.

By comparison, paloverde displays no clear trend with distance but is slightly bimodal with clusters at about 120 and 230 m of channel distance (Fig. 4.1.4). The medium channel distance for live and dead paloverde is 147 m. There is an apparent trend in the increase in the frequency of dead paloverde at channel distances less than about 160 m relative to the total number of dead paloverde.

Analysis of Plant Scars

A ubiquitous feature common to YPG and surrounding areas across the more arid reaches of the desert Southwest are features we call plant scars (Fig. 4.1.6). These features form conspicuous and highly visible features across the desert piedmonts common to YPG. For reasons discussed below, we think that the formation and distribution of these plant scars reflect long-term changes in the desert ecosystem. Examination of USGS 7.5' (1:24,000) orthophotoquads of southwestern Arizona, and field observations across the southwest U.S. indicate that these features occur in multiple locations across the Mojave and Sonoran Deserts. Furthermore, these observations indicate that plant scars are largely restricted to areas that receive less than approximately 150 mm average annual precipitation.

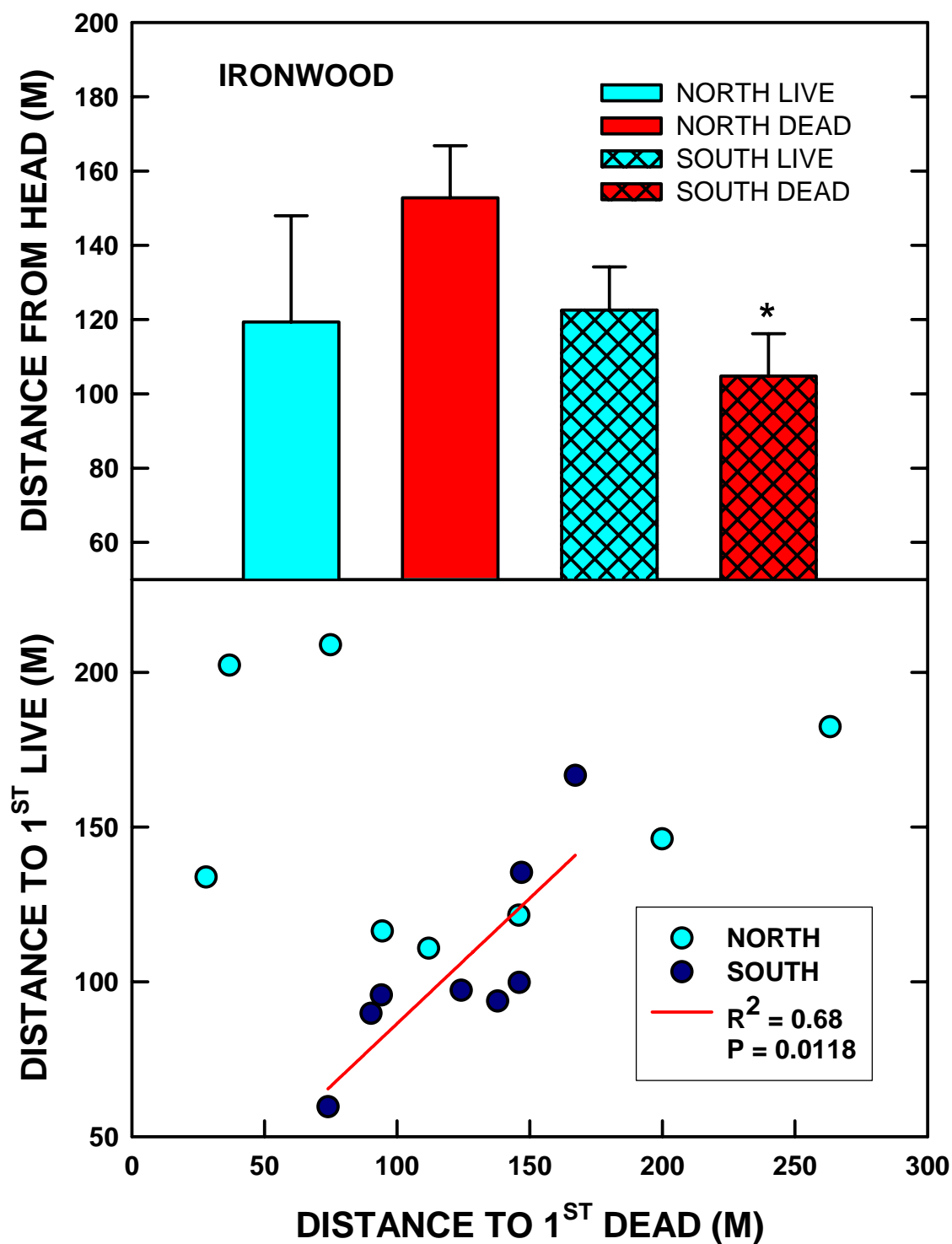


Figure 4.1.5. Relation between distance along first-order channel from top of drainage basin to first live and first dead paloverde and ironwood trees.

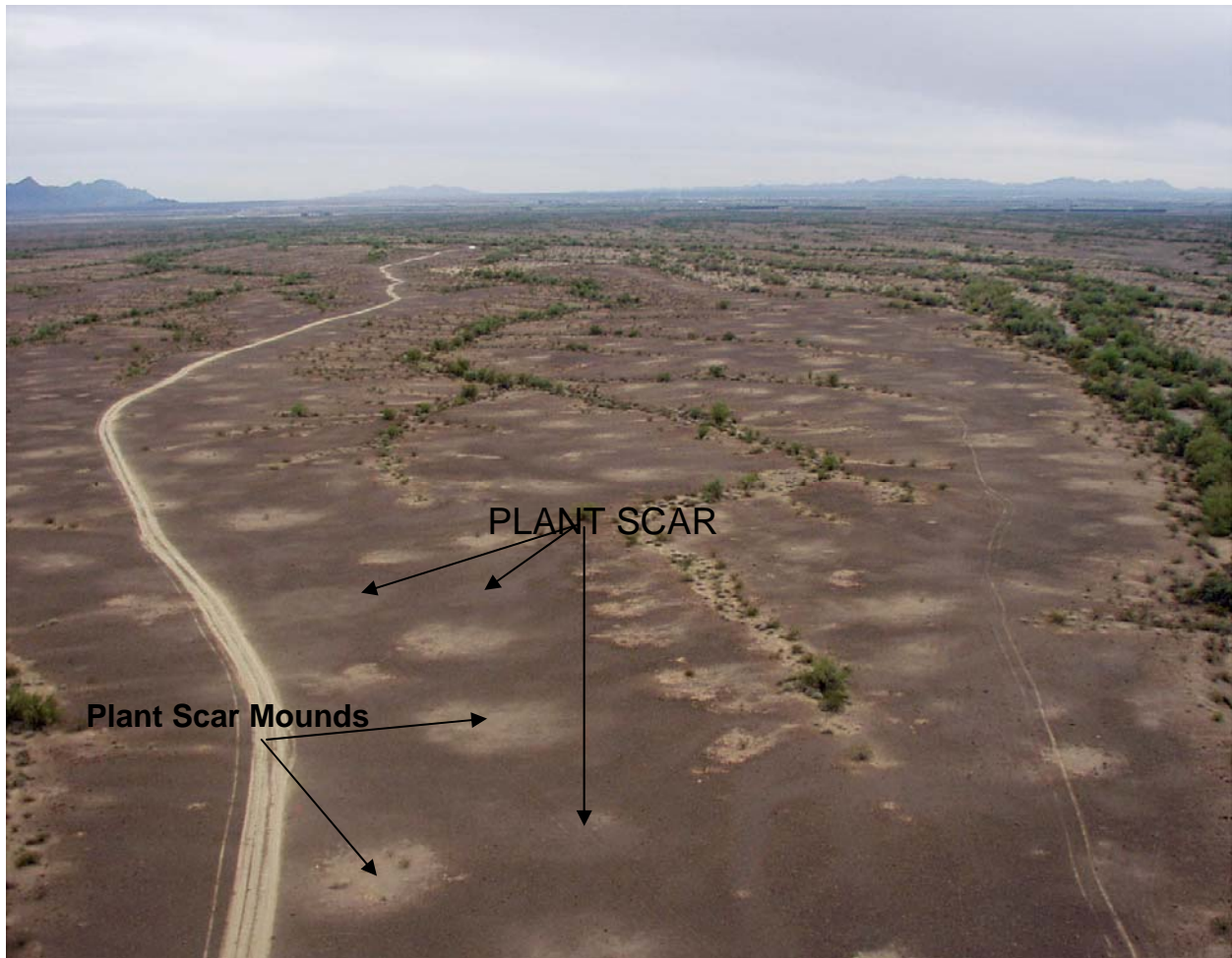


Figure 4.1.6. Oblique aerial view of plant scars. Two basic types of scars have been identified across the areas of desert pavement: plant scar mounds (light-colored circles) and plant depressions (faint, dark colored circles).

Plant scar morphology and setting

We have identified two basic types of plant-related landscape features: plant scar mounds and plant scar depressions. Plant scar mounds are the most conspicuous type of plant scar across the wide, flat surfaces of darkly varnished desert pavements (Fig. 4.1.7a). These plant scars consist of slightly elevated, light-colored circular mounds ranging from a few meters to at most 10 m in diameter. The center portions of the mounds are commonly elevated from a few centimeters to about 30 cm above the planar surface of the surrounding desert pavements. The light color of the mound surface is due to the absence of varnished coatings on clasts and also to the exposure of whitish pieces of carbonate-coated clasts and pebbles brought to the surface by the excavation activities of burrowing rodents. The dimensions of the plant scar mounds are similar to the size of the circular area and the height of the mounds associated with stands of active shrubs (Fig. 4.1.7b). Plant scar depressions are similar in diameter to plant scar mounds, but the center of the mound forms a very shallow, saucer-like depression that is a few centimeters below the surrounding planar surface (Fig. 4.1.7c). Plant scar

depressions are commonly covered with either a layer of loose pebbles or weakly-to-moderately developed desert pavement with a coating of rock varnish. The varnish is less developed in terms of thickness and dark coloration relative to areas of surrounding pavement. Plant scar depressions have features very similar to cultural resource features commonly referred to as sleeping circles or cleared circles (Fig. 4.1.7d).

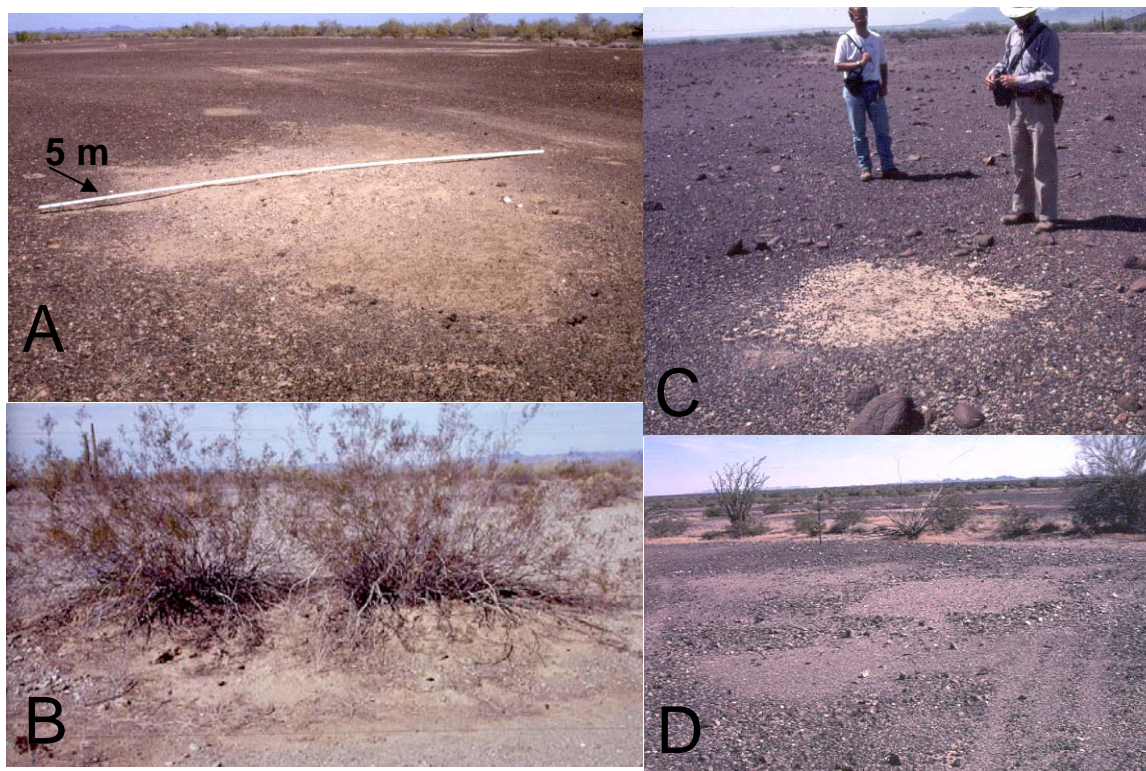


Figure 4.1.7. Examples of plant scar features: (A) Typical plant scar mound, (B) active mound with creosotebush, (C) plant scar depression with partial cover of desert pavement, and (D) features classified as cleared or sleeping circles. Clear circles, which are considered cultural resource features, show features common with plant scars.

Field Evidence for the Formation of Plant Scar Mounds

Many plant scar mounds have either surface signs of very recent faunal burrowing, woody remains of dead shrubs, or patchy coverage by desert annuals; however, nearly all circular mounds are currently devoid of living shrubs. These low mounds apparently originally formed beneath canopies of long-lived perennial woody plants.

Creosotebush is most likely the shrub beneath which most plant scar mounds formed. Individual creosotebush plants can be extremely long-lived and may persist for many centuries or even several thousand years (Whitford, 2002). Very old, large plants can attain basal diameters of several meters. This great longevity together with the protective architecture provided by the above-ground canopy and underground root system offers a favorable microenvironment for long-term occupancy by burrowing mammals, including kangaroo rats, pocket mice, and the larger ground squirrels. Over the long term, burrowing by rodents reduces soil bulk density through movement of soil to the surface,

thereby increasing soil volume and producing an elevated soil mound beneath the plant canopy. The formation of a relatively large, elevated mound with these features probably requires the temporally unbroken presence of a large creosotebush plant and associated burrowing mammals for many centuries to millennia.

Excavations of the soil underlying plant scar mounds and plant scar depressions indicate an abundance of soil features associated with bioturbation. Features such as open animal burrows and krotovina (animal burrows back-filled with soil material) are common below both plant scar mounds and plant scar depressions (Fig. 4.1.8). Soil horizons, especially horizons characterized by the

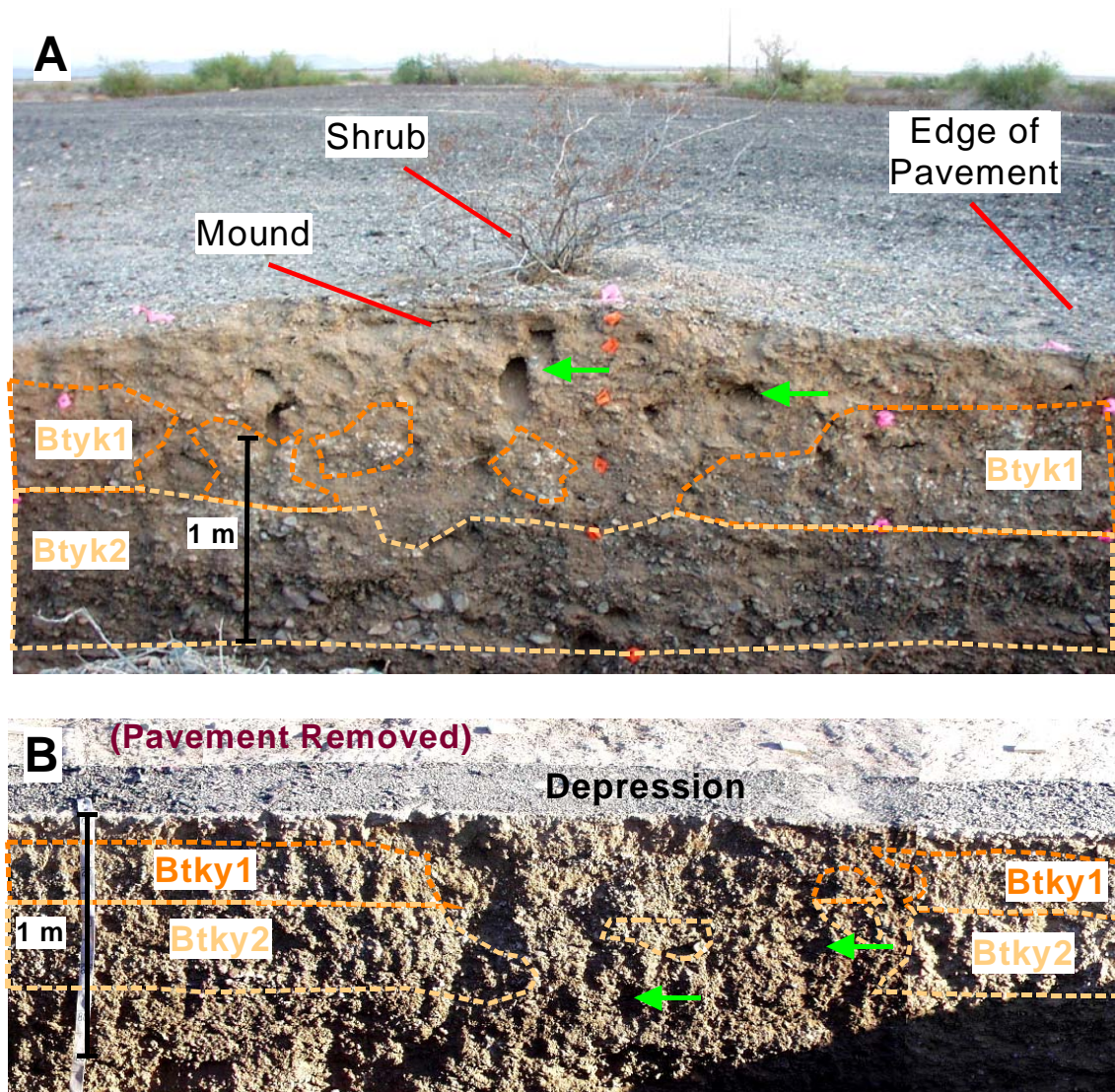


Figure 4.1.8. Trench exposing soil underlying plant mound scar (A) and plant scar depression (B) showing examples of krotovina and open animal burrows (green arrows) and truncated soil horizons (tan-reddish dashed lines). Soil horizons have been truncated by faunal burrowing.

pedologic accumulation of iron oxides and calcium carbonate, are clearly disrupted below the mound and scar center by faunal and floral mixing. Evidence of thorough soil mixing indicates that plant and animal activity persisted for long periods of time.

After the death and disintegration of the original shrub beneath which the mound formed, the mound continues to be a localized spot of biological activity compared to the surrounding, barren desert pavement, although the level of activity is reduced considerably relative to periods with extensive shrub cover. In a sample of ninety plant scar mounds surveyed in March 2000 within the study area, 62% were occupied by very small, juvenile creosotebush plants. These plants, however, typically had basal stem diameters less than 1 cm and canopy heights and diameters less than 50 cm. These very small plants probably represent ones that have established within the past several decades and are not the original plants beneath which the mounds developed. Plant scar mounds consistently lack the presence of any large, living creosotebush, or woody remnants that could possibly be derived from an original shrub.

In years with abundant winter precipitation, the mounds typically support abundant ephemeral plant growth. Seed production by these plants probably supplies food for seed-eating rodents, thereby promoting the continued, but somewhat reduced, bioturbation of the mound. This level of faunal mixing is probably constrained to the uppermost few centimeters of the surface. This continued bioturbation tends to maintain the light-colored surface of the mound in comparison to the dark background of varnished desert pavement.

Age Relations Among Plant Scars and Hypothesized Timing of Episodes of Shrub Mortality

Soil and geomorphic relations indicate that the ages of the mound surfaces vary. The plant scar mounds represent the youngest plant scar morphology and the initial degradation of the mound following the most recent and intensive level of biologic activity (Fig. 4.1.10A). Although considerable biological activity (largely due to ephemeral plants) continues on the plant scar mounds, with the absence of a protective plant canopy, these areas no doubt experience a net erosion and decline in height over time, progressing toward a reduction in the size of the mound (Fig. 4.1.10B). The absence of any large woody debris on the mounds derived from large creosotebush plants (or other shrubs) suggests that the original plants beneath which the mounds formed died nearly a century ago or more, given the slow rates of decomposition of woody materials in this extremely arid zone. The relatively uniform morphology and appearance, and the ubiquitous presence of the plant scar mounds on fan surfaces, further suggests a regionally synchronous environmental change as the trigger responsible for the death of the original shrubs.

Continued degradation of the mound, probably in conjunction with decreasing biologic activity, results in the eventual formation of a nearly smooth plant scar that has a lag layer of light-colored pebbles (Fig. 4.1.10C). With increasing time, this pebble lag gives way to the development of a weak to moderate desert pavement consisting of interlocking clasts and the formation of the shallow, saucer-like depression (Fig. 4.1.10D). The morphology of the pavement-covered plant scar depressions indicates that they may be several thousands of years old. Research has shown that the extent of varnish coatings observed on surface clasts in some of the plant scar depressions is similar to the degree of varnish found on 4,000–12,000-year-old alluvial fan surfaces across the southwestern U.S (Bull, 1991; McDonald, 1994).

SPATIAL DISTRIBUTIONS OF PLANT SCARS

Although plant scar mounds and plant scar depressions are found on the same surfaces of Pleistocene alluvial fans, their spatial distributions differ with respect to the surface drainage network. Distances were measured for 586 individual plant scar mounds, forty-nine plant scar depressions, and 350 random points to the nearest edges of first-order channels.

**Bioturbation from
Roots and
Burrowing
Rodents**

**Deflation and
Collapse of
Mound**

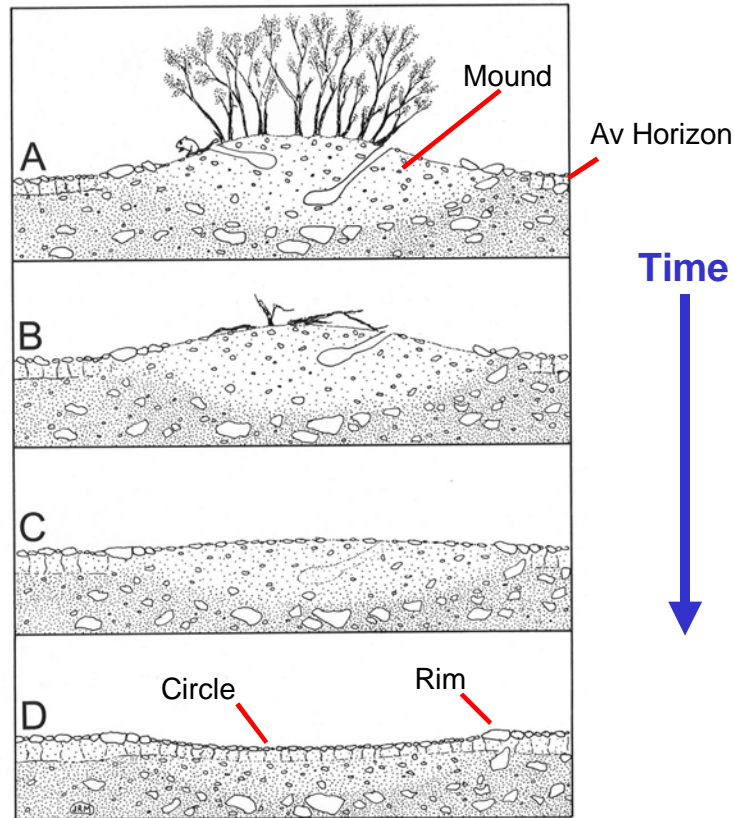


Figure 4.1.10. Schematic diagram showing sequence of events in formation of plant scars. (A) Active faunal and floral bioturbation creates mound by bringing soil to surface. (B) Onset of plant mortality and loss of bioturbation increases erosion of soil from the mound and increasing subsidence of mound. (C) New cover of stones leads to formation of a weak pavement. (D) Continued subsidence leads to formation of a plant scar depression.

Neither the mounds nor depressions are randomly distributed with respect to the distance from the nearest flume. Furthermore, the distributions of the mounds and depressions differ sharply (Fig. 4.1.11). Even though the means of the distance measurements for plant scar mounds and random points are nearly identical, the shapes of the two distributions differ significantly (Fig. 4.1.11a and Fig. 4.1.11b). The plant scar mound measurements have a much smaller variance (i.e., a much narrower, peaked distribution) than the measurements from the random points (F-test for equality of variances, $P < .01$). This difference in the variances of the two distributions is due to the sharp, well-defined peak between 5 and 15 m in the distance measurements from plant scar mounds and the lack of such a well-defined peak in the measurements from random points. Furthermore, the distance measurements for the plant scar mounds contain very few measurements within 5 m of flumes or

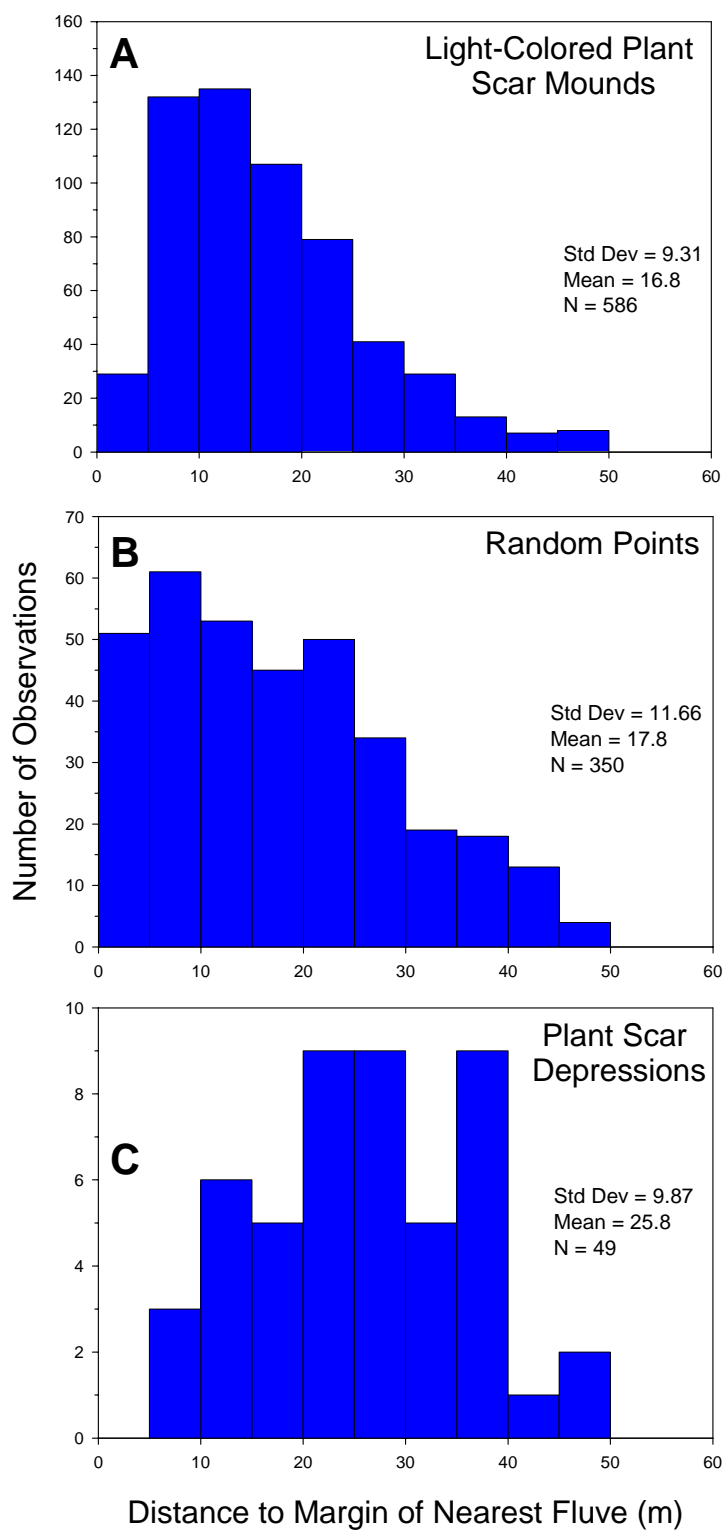


Figure 4.1.11. Distribution of distances measured to the nearest margin of the nearest flume for (A) plant scar mounds, (B) randomly distributed points, and (C) plant scar depressions. Plant scar depressions occur closer to the center of the interflumes whereas plant scar mounds occur closer to the first-order channels.

further away than 25 m. The conclusion from this comparison is that the white plant scar mounds are non-randomly distributed within the interfluvial areas and are concentrated in a rather narrow swath nearer the fluvial channel than would be expected if the mounds were randomly distributed.

In contrast, the faintly visible plant scar depressions were, on average, located further from the edges of fluvial channels than the younger plant scar mounds or random points (Fig. 4.1.11C). This contrasting spatial distribution of white plant scar mounds and the depressions was also observed in reconnaissance of other areas on the YPG. Soil and geomorphic relations indicate that the varnished depressions represent older plant scars (Fig. 4.1.7 and Fig. 4.1.10), and the greater predominance of these depressions away from fluvial channels implies that a first wave of plant mortality in these landscapes occurred in the more centrally located parts of interfluvial areas. This earlier wave of mortality was apparently followed by a more recent episode that occurred nearer the margins of the interfluvial areas. In other words, the differential distributions of these two types of plant scars with presumably different ages imply that the distribution of vegetation on these fan surfaces has become increasingly “contracted” over time, eventually yielding the nearly vegetation-free interfluvial areas present today.

DISCUSSION

Results from analysis of vegetation along first-order channels and the origin and development of plant scars provide important information about how natural changes in environmental settings will impact ecosystem health. Overall, results indicate that environmental factors that control the surface flow of water are the primary elements controlling ecosystem health. Several factors, however, especially climatic variation and alteration of surface-contributing source areas, will control water availability. Recognition of these factors is required to best monitor ecosystem health. Results of this study suggest at least two important environmental factors, surface water flux and historic and prehistoric climate change that appear to strongly control ecosystem health.

The Role of Surface Water in Ecological Condition

Results presented above clearly demonstrate that the flux of surface water flow along first-order channels is a primary factor influencing ecosystem health. Simple relations such as the considerable increase in tree and shrub mortality down channel from road constrictions or from large areas of degraded soil and desert pavements demonstrate the critical relationships between the episodic flow of surface water and the density and diversity of desert vegetation. One important aspect of this relation is that it validates that a *surface* source of water is required for maintaining important tree and shrub species. Plant-available water, therefore, is not likely to be maintained by either access to shallow ground water or by the lateral, down gradient flow of vadose zone water from upstream sources. Changes to the soil surface that limit surface runoff and decrease episodic channel flow will ultimately and severely impact desert vegetation.

Spatial relations among the distribution of important tree species also support the dominant role that surface water has in supporting vegetation. Larger tree diameters associated with larger drainage basin areas indicate that tree diameter corresponds to a greater flux of surface runoff into first-order channels. There is an equally important relationship between growth and leaf area, which is usually scalar in desert plants. Bigger trees maintain a bigger transpirational leaf area, since the ratio of leaf-area to sapwood area is usually consistent (Pataki et al., 2000; Smith et al., 1995 missing). This relation suggests that larger trees may be susceptible to mortality if environmental changes limit the

supply of surface water. Ironwood has a greater average tree diameter than the average diameter of paloverde, suggesting that ironwood is more susceptible to mortality. Interruptions of effective transmission of surface water to the subsoil (recharge of soil moisture through runoff) will increase the chance for mortality because maintaining the water cost is too great to match respiratory load. Overall, water use in paloverde is much more constrained, since most of the physiological activity is through the stem, which has much higher WUE (described in more detail in section 4.2).

Plant Scars: Indicators of Natural Environmental Change as a Driver of Plant Mortality

Shrub mortality resulting in plant scar formation appears to have occurred in at least two principal episodes, as indicated by the different spatial distributions of the two kinds of these surface features (mounds versus depressions). We postulate that the plant scar mounds represent the geologically recent wave of mortality (i.e., within the last few centuries), whereas the varnished depressions apparently represent an earlier episode (i.e., over the last few millennia). Long-term changes in climate and soil development may be also responsible for the development of the plant scars.

The older varnished depressions probably represent the consequences of a significantly earlier climate change. One possibility is that the oldest plant scar depressions are associated with shrub mortality that occurred at the major climate transition from the Pleistocene to the Holocene approximately 11,000 years B.P. During this time period, vegetation across the Southwest U.S. and northern Mexico was undergoing regional changes in distribution with the onset of increasing aridity (Van Devender, 1990; Bull, 1991). Studies of fossil packrat middens from the Sonoran Desert region of southern Arizona and California at elevations similar to YPG indicate that an increase in creosotebush (and associated shrubs) began after about 12,500 years B.P., in conjunction with an increase in aridity (McAuliffe and Van Devender, 1998). A second interval of pronounced climate change resulting in a reduction in effective precipitation occurred approximately 4000 years ago B.P. At this time it is not clear if one or both of these intervals of climate change is responsible for the onset of plant scar formation; however, as discussed above, geomorphic relations indicate that the pavement-covered plant scar depressions are probably at least a few thousand years old.

It is difficult to assign definitive periods of climate change to the formation of the plant scar mounds. We postulate that these mounds are likely to be at least a hundred years old due to their mound morphology and lack of woody remains. The lack of woody remains is significant because decomposition of wood in arid environments is extremely slow. Examination of a few older photographs, primarily those of military activities at YPG from the 1940s and 1950s, indicate a lack of vegetation on the mounds half a century ago. Several possible periods of regional climate change may be responsible for increased development of mounds (i.e., increased shrub activity and bioturbation (A in Fig. 4.1.10), eventually leading to the subsequent mortality of shrub cover (B in Fig. 4.1.10). First, a regional increase in precipitation occurred about 400 years ago that is related to ENSO (El Niño/Southern Oscillation), and that resulted in a regional increase in frontal storm activity, regional floods, and an increase in effective soil moisture (Enzel et al., 1989; Ely et al., 1994; McDonald et al., 1996; Ely, 1997). A second period of pronounced flood activity in southern Arizona occurred between about 1750 and 1900 (Redmond et al., 2002). In both cases, it is possible that increases in surface runoff and in effective soil moisture resulted in an increase of faunal mixing and construction of the plant scar mounds. A subsequent decrease in effective precipitation then forced an increase in shrub mortality, leading to the formation of nearly uniform plant scar mounds.

Although it is likely that the hypothesized episodes of plant mortality are associated with periods of increasing aridity, lack of moisture *per se* may not be the only mechanism that contributed to the widespread, apparently synchronous mortality of adult plants. Soils beneath the desert pavements on Pleistocene alluvial fans where the plant scars are found are strongly saline, even within a few centimeters of the surface. Eolian deposition is the source of these salts. Under the present-day, extremely arid conditions of this area, the small amount of precipitation is insufficient to leach these soluble salts to deeper levels in soils of Pleistocene fan deposits where they would not seriously affect the performance of non-halophytic plants. Substantial quantities of salt have accumulated at rather shallow levels on these older fan surfaces because these soils contain fine-textured soil horizons (Av, Bt horizons) that impede the surface infiltration and downward percolation of water. Studies in other arid regions, such as the Negev Desert of Israel, have shown that eolian inputs of soluble salts can rapidly increase soil salinity in extremely arid zones where such insufficient leaching occurs.

Under conditions of greater effective precipitation during the Pleistocene, it is likely that soils on older fan surfaces were sufficiently leached of salts to allow the growth of non-halophytic plants such as creosotebush. However, with climatic drying associated with the Pleistocene-Holocene transition, substantially reduced leaching of salts could have led to relatively rapid, shallow accumulations of salts in the most central parts of interfluvial areas where plants apparently first disappeared. A similar pattern appears in the additional increase in climatic aridity that occurred at the mid-late Holocene transition after about 4000 years ago B.P. that could have led to increasing shallow salt accumulations in areas even closer to fluvial channels.

Two possible mechanisms that caused plant mortality—direct effects of reduced precipitation and increased soil salinity levels—are not mutually exclusive hypotheses. The accumulation of salts as proposed would have compounded the direct, negative effects of reduced precipitation on plant performance. It is likely that both mechanisms acted in concert to produce the apparently synchronous, regionally widespread episodes of shrub mortality that eventually yielded the surface features of plant scar mounds and plant scar depressions.

CONCLUSIONS

Detailed conclusions and implications for historic and pre-historic changes in vegetation along channels are provided in section 6.0 of this report. The following list summarizes key findings:

- (1) There is a profound decrease in native vegetation where surface runoff is blocked (e.g. road across wash), or there is destruction of desert pavement and other similar soils that generate surface runoff. Runoff and subsequent channel flow is required for the maintenance of biodiversity along ephemeral drainages.
- (2) Trees along upper reaches of first-order drainages may indicate a recent increase in mortality, but there is no overall clear pattern of historic changes in vegetation.
- (3) Results suggest that there is a relation between basal tree diameter and upstream size of source area, and ironwood has a greater average tree diameter than the average diameter of paloverde along first-order channels. Larger trees may be susceptible to mortality if decrease in supply of surface water.

- (4) The mortality of shrubs has resulted in the formation of numerous plant scars. Mortality appears to predate military land-use. Development of plant scars is due to natural environmental change, ranging from decades to centuries, and not military activities.

4.2 Soil Hydrology: Relation Among Desert Pavements, Surface Runoff, and Vegetation Response Along First-Order Drainages

Integration of ecological investigations with geoscientific research on landscape dynamics and soils have proven essential for interpreting much of the ecological phenomena that occurs on the extensive desert piedmonts of the Mojave and Sonoran Deserts (McAuliffe, 1991, 1994, 1995; McAuliffe and McDonald, 1995; Kemp et al., 1997). Major soil-forming processes in these arid environments include accumulation and vertical redistribution of clay, silt, calcium carbonate, and soluble salts, and the incorporation of these materials into well-developed soil horizons. Recent research focused on desert soil systems has produced many new models regarding how soil and landscape processes operate, including the accumulation of desert dust in soils, formation of desert pavements, soil water balance, and short- and long-term landscape stability (c.f. Bull, 1991; McDonald et. al., 1999; Reheis et. al., 1995; McFadden et. al., 1998). Understanding the control of the soil and landscape on the flux of water is critical to ecosystem studies in desert environments because soil water availability is the principal factor limiting many ecosystem processes in warm deserts (Ehleringer, 1985; Smith et. al., 1997). Different soil conditions greatly modify the precipitation signal by affecting surface and subsurface infiltration, depth of moisture storage, and the temporal persistence of plant-available moisture (Noy-Meir, 1973). Consequently, the accurate prediction of many ecosystem responses in deserts requires knowledge of both the spatial distribution of soils and the diverse hydrologic behaviors of various soil types.

The greatest hindrance to understanding the relationships among desert plant dynamics, surficial processes, soil water dynamics, and prediction of both natural and anthropogenic impacts of environmental change is the limited information on soil water dynamics and soil-geomorphic properties. Detailed knowledge about the hydrological behaviors of different soils and geomorphic settings is needed to advance the investigation of many ecological processes, from the whole plant to landscape-level ecosystem scales. Furthermore, future ecological changes in arid regions brought about by regional or global environmental alterations, including impacts related to military activities, will likely be mediated through soil hydrological changes and associated vegetation response.

The purpose of this section is to demonstrate the linkages among soil properties, surface water hydrology, and vegetation response along first-order drainages common to the extensive alluvial piedmont surfaces of the lower Sonoran Desert.

METHODS

Experimental Design

The evaluating relations between soils and vegetation and related ecophysiological response were evaluated through characterization of soil-hydrologic-plant linkages

among six first-order drainage basins that range in size from about 10,000–48,000 m². The six drainages are located across two extensive alluvial terraces. The upper three drainages (hereafter, north drainages) are labeled N1, N2, and N3; and the lower three drainages (hereafter, south drainages) are labeled S1, S2, and S3.

We separated each of the six studied drainages into two plots (see Fig. 3.0.1). One plot was located along the uppermost reach of the first-order drainage (hereafter referred to as the upper channel) that has ironwood and paloverde trees. A second plot was located along the lowermost extent of the first-order channel (hereafter referred to as the lower channel) where trees lay just up-gradient from the distal end of the first-order channel.

SOIL CHARACTERIZATION

Physiochemical properties

Soil physiochemical properties were determined at eleven sites within two drainages. Soils were described and sampled at four locations (pavement, swale, upper channel, and lower channel) within two of the six study plots (N1 and S3). Additional soil information was collected from 1.5⁺ m deep pits excavated into the desert pavement, upper and lower channels of a first-order channel adjacent to drainage N1.

Soil morphology was described using standard Soil Survey Staff (1998) methods and modified using soil-geomorphic information as listed in Birkeland (1999). Detailed soil descriptions included normal soil morphology with an emphasis on horizontal and vertical variation in key properties that influence soil-water balance, including surface-cover and geomorphic position, horizon thickness and boundaries, texture, structure, pores, and roots. Laboratory measurements included standard techniques for particle-size determination (Gee, 2002), soluble salt content (Rhoades, 1996), and pH (Thomas, 1996). Bulk density was measured either by wax-coated clod or in situ excavation method (McDonald, 1994; Grossman and Reinsch, 2002).

HYDROLOGIC PROPERTIES

We used four methods to characterize soil hydrology. Near-saturated hydraulic conductivities of surface soil horizons were estimated in the field based on measurements using a tension disk permeameter (Perroux and White, 1988), providing a continuous supply of water at a constant, near-saturated tension of -2 cm. (Fig. 4.2.1). Hydraulic conductivity at -2 cm tension [$K(h)$] was computed using the empirical relationship developed by Zhang (1997). Cumulative infiltration is fitted against the square root of time using the power function:

$$I = C_1 t + C_2 \sqrt{t} \quad [1]$$

where I is cumulative infiltration (cm sec⁻¹), C_1 and C_2 are curve-fitting parameters, and t is time (sec). Infiltration from a circular source in three dimensions is a combination of both horizontal movement or sorptivity (C_2) and true vertical infiltration (C_1). Thus, the field infiltration from a disk permeameter overestimates true infiltration and must be corrected for sorptivity by the following equation in order to calculate hydraulic conductivity:

$$K(h) = \frac{C_1}{A} \quad [2]$$

where $K(h)$ is the hydraulic conductivity (cm sec^{-1}) at the supply tension h ($-\text{cm}$). C_1 is fitted from Eq. 1 and equal to the uncorrected infiltration rate (cm sec^{-1}). The dimensionless correction factor, A , is derived from the empirical relationship (Zhang, 1997):

$$A = \frac{11.65(n^{0.1} - 1)e^{2.92(n-1.9)ah}}{(\alpha r)^{0.91}} \quad n \leq 1.9 \quad [3]$$

$$A = \frac{11.65(n^{0.1} - 1)e^{7.5(n-1.9)ah}}{(\alpha r)^{0.91}} \quad n < 1.9 \quad [4]$$

Both n and α are water-retention parameters derived based on the van Genuchten (VG) retention function. Van Genuchten parameters were estimated by a neural network prediction model (Rosetta Lite V. 1.0, U.S. Salinity Lab, Riverside, California). The model predicts VG parameters based on sand, silt, and clay content. The correction is defined by the disk permeameter radius (r) in cm and the supply tension (h).

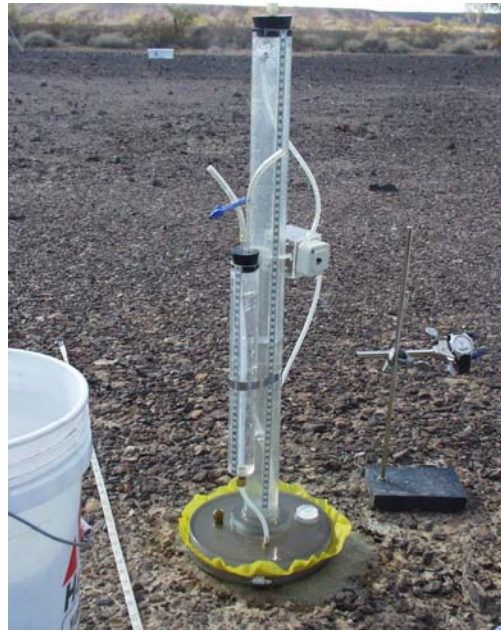


Figure 4.2.1. Near-saturated hydraulic conductivities of surface-soil horizons were estimated in the field based on measurements using a tension disk permeameter.

We measured soil moisture using a model 6050X1 Trase time-domain reflectometry (TDR) system and buriable 20 cm waveguides (Soil Moisture Equipment Corporation, Santa Barbara, California). Each waveguide was horizontally inserted into undisturbed soil at about 5 and 30 cm depths at four sites (pavement, swale, upper channel, and lower channel) in the N1 and S3 drainages. Excavated soil was carefully replaced to prevent large changes in soil hydrology.

Surface runoff was qualitatively monitored at two sites on drainage basin N1 (Fig. 4.2.3). One plot was located on a level soil surface and a second plot was located on a gently sloping ($\sim 2\text{--}3^\circ$ south) surface. The plots were about 30 m apart and were each located on a soil surface with well-developed desert pavement. Runoff plots were constructed by carefully inserting ten-gauge aluminum

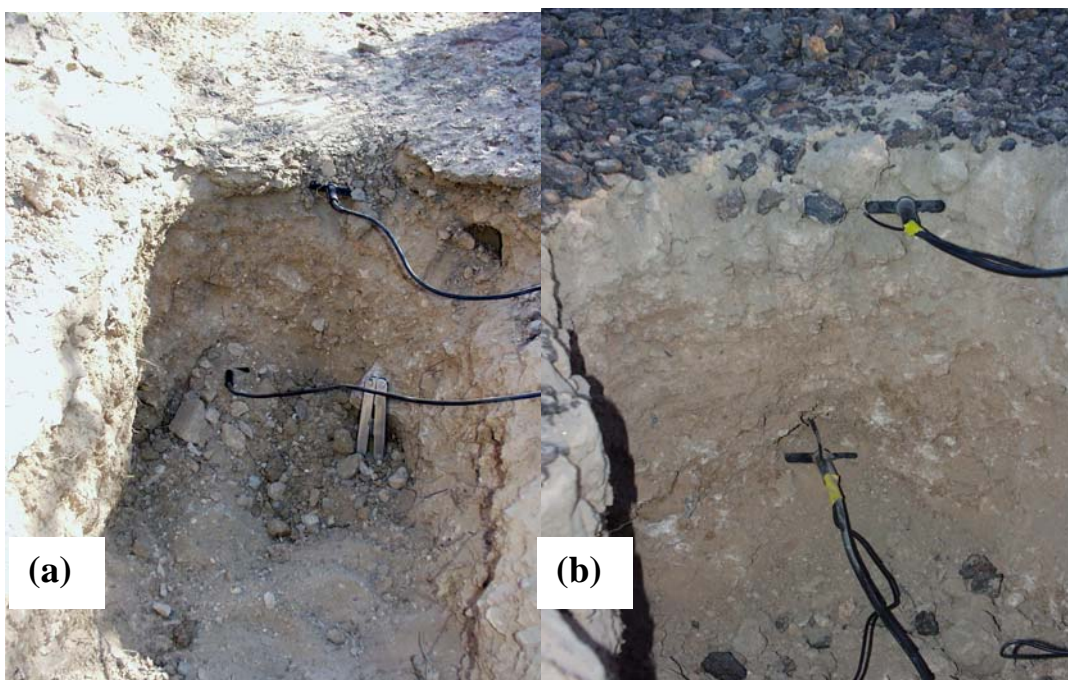


Figure 4.2.3. Soil moisture was measured with time-domain reflectometry (TDR) using Trase buriable 20 cm waveguides. Photographs show typical installation of soil TDR probes into lower channel soil (A) and soil underlying desert pavement (B).

flashing ~ 5 cm into the soil with limited disturbance to the desert pavement. The inside of the flashing was sealed using asphalt roofing sealant. Each runoff plot enclosed about 1 m^2 . Runoff was collected into four liter plastic milk jugs buried below the soil surface. The milk jugs were periodically inspected to determine if runoff had occurred.

ELECTROMAGNETIC INDUCTION

Electromagnetic induction (EM) is a non-intrusive technique for measuring the apparent electrical conductivity of the soil. The measured value of soil electrical conductivity obtained from electromagnetic induction is a function of soil texture, salinity, water content, and soil temperature (Kachanoski et al., 1988; Sheets and Hendrickx, 1995). Because soil factors such as texture and salinity may have some local spatial variability, the EM cannot make definitive “measurements” of soil moisture at a given location. Since soil salt content and texture do not change seasonally,

however, changes in relative electrical conductivity between survey dates may be considered primarily a function of soil water content and temperature. Kachanoski et al. (1988) found that the spatial variations of bulk soil electrical conductivity were highly correlated to soil-water content in soils with low concentrations of dissolved electrolytes. Soil ground conductivity was measured using a ground conductivity meter (Geonics, Model EM-38, Mississauga,

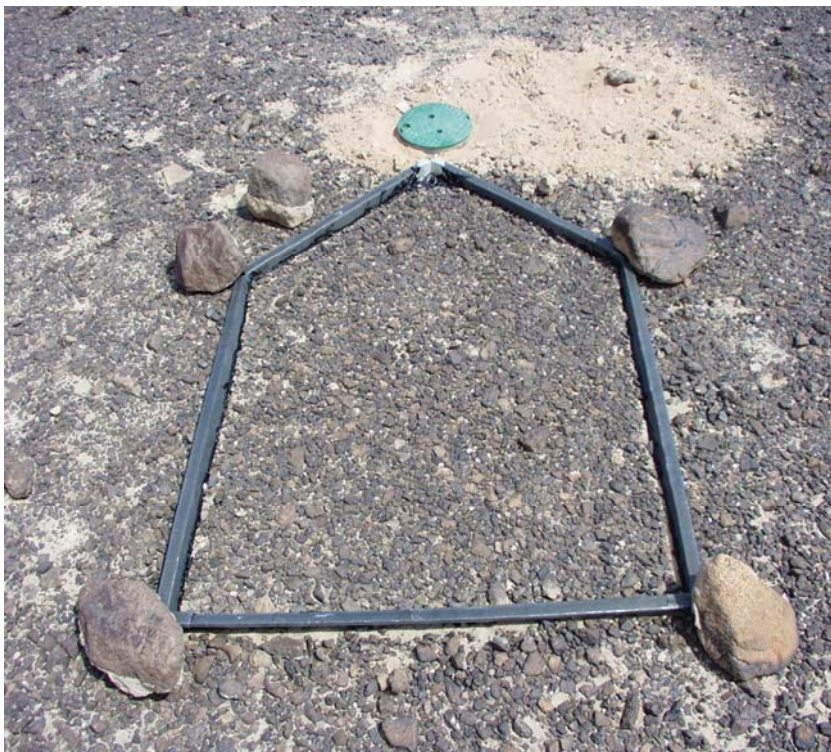


Figure 4.2.3. Runoff plot constructed on desert pavement. Runoff area is approximately 1 m². Runoff was collected into a four liter plastic milk jug buried below the soil surface (under green cap at top of photograph).

Ontario, Canada) (Fig. 4.2.4). Measurements were made in both the vertical and horizontal modes, which correspond to depths of 1.5 and 0.75 m respectively. This technique provides useful information on the vertical distribution of soil moisture in a soil profile and has the additional advantage of providing spatial data over broad areas in a short time. Sheets and Hendrickx (1995) found that when the EM was calibrated with neutron scattering, it could effectively estimate changes in soil moisture over a wide area. Kachanoski et al. (1988) had similar success in comparing EM measurements with TDR and gravimetric moisture measurements.

Soil ground conductivity was measured along four transects that crossed the N1 and S3 drainages perpendicular to the channel. The four transects were evenly distributed between the upper and lower ends of the first-order drainage basin. Wooden stakes were used to mark the beginning and end of each transect. Measurements were taken at ~3m intervals (two paces) and were taken in the horizontal and vertical mode and at ground level.

ECOPHYSIOLOGICAL CHARACTERIZATION

Water Potential

Predawn and mid-day xylem water potentials were measured in the field using a Scholander type pressure chamber (Plant Moisture Stress Inc, Corvallis, Oregon). Water potential data was collected on creosotebush (*Larrea tridentata*), ironwood (*Olneya tesota*), and blue paloverde (*Cercidium floridum*). Sampling was conducted within six drainage basins, with branches of pre-dawn



Figure 4.2.4. Soil ground conductivity was measured using a ground conductivity meter (Geonics Ltd., Model EM-38, Mississauga, Ontario, Canada). Electromagnetic induction (EM) is a non-intrusive technique for measuring the apparent electrical conductivity and soil moisture content of the soil.

sampled plants marked for midday water potential and photosynthetic gas exchange measurements. Water potential was measured for a stand of vegetation (three creosote shrubs, one paloverde, and one ironwood) located at the uppermost and lowermost portions of first order channels (see Fig. 3.0.2). These species, which differ in longevity, stress tolerance, and rooting habit, are distinctly sensitive to soil-water deficits and thereby provide ideal comparisons for indicating alterations to soil hydrology and related environmental conditions.

Measurement of plant water potential provides a direct measurement of plant available soil moisture that is integrated across the entire plant root system. Evaporation from leaves creates a negative tension as water is pulled out of the leaf mesophyll; this process moves water up through the xylem of the stem and roots, and out of the soil. Cutting a stem breaks the water column, which rebounds above and below the cut. The excised stem is placed with the cut end extruding from a sealed pressure chamber fitted with a pressure transducer (Fig. 4.2.5). Inert N-gas is slowly introduced into

the chamber, and when water appears at the cut surface of the stem, the pressure applied is exactly that of the xylem water potential at the time of the cut. Xylem water potential shows diurnal variation, becoming more negative as temperature and evaporation increase through the day, and seasonal variation as soil-water reserves become replenished or depleted. Predawn estimation of xylem water potential (ψ_{pd}) provides a reliable indicator of the soil water status. At late night, stomatal closure and low temperatures result in minimal evaporative loss. Under such conditions, the plant and soil can reach equilibrium, and the xylem water tension reaches its highest (i.e., least negative) values that closely reflect the water status of the soil volume integrated by the rooting volume (Nobel, 1991).



Figure 4.2.5. Predawn and mid-day xylem water potentials were measured in the field using a Scholander type pressure chamber (Plant Moisture Stress, Corvallis, Oregon). Photograph shows detached chamber cap with small cut branch from a creosote bush inserted into an air-tight flange.

WEATHER DATA

Weather data used in this study is from a U.S. Weather Service station (station #40927) maintained in the Blythe, California, airport (about 30 km north of the study site). Weather data from 1995 to 2003 was used to evaluate short- and long-term trends in soil moisture and runoff. A recording rain gauge was installed at the study site, but this gauge was stolen early in the project and was not replaced.

RESULTS

Soil Physiochemical Properties

Soil properties strongly contrast between the pavement-covered surfaces and the first-order channels (Fig. 4.2.6a). A moderate to well-developed desert pavement covers most of the soil surface surrounding the first-order channels (Fig. 4.2.7a). This pavement consists of a single layer of clasts at the surface and forms an interlocking mosaic. The uppermost soil horizon underlying the desert

pavement has a 4–6 cm thick vesicular (Av) horizon with well-developed columnar and platy soil structure and abundant vesicular pores (Fig. 4.2.6b). The character of the desert pavement and Av

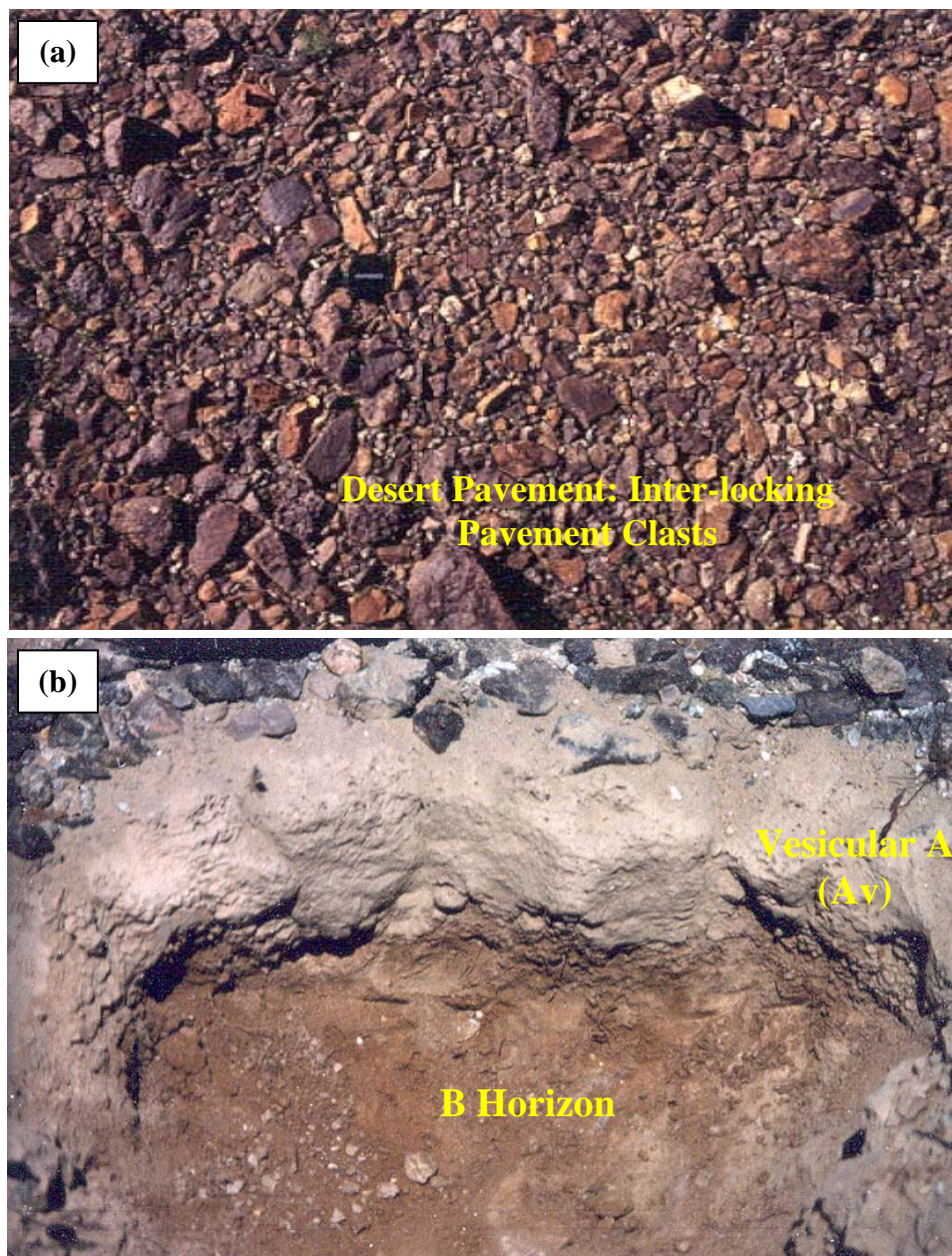


Figure 4.2.6. Photograph of desert pavement (a) and the underlying Av horizon and B horizon (b). Pavement consists of a nearly continuous interlocking of surface clasts, largely one clast in thickness. Av horizon is a 3–10 cm thick layer that is gravel poor and rich in silt and clay. The Av horizon is formed by long-term accumulation of aerosolic dust.

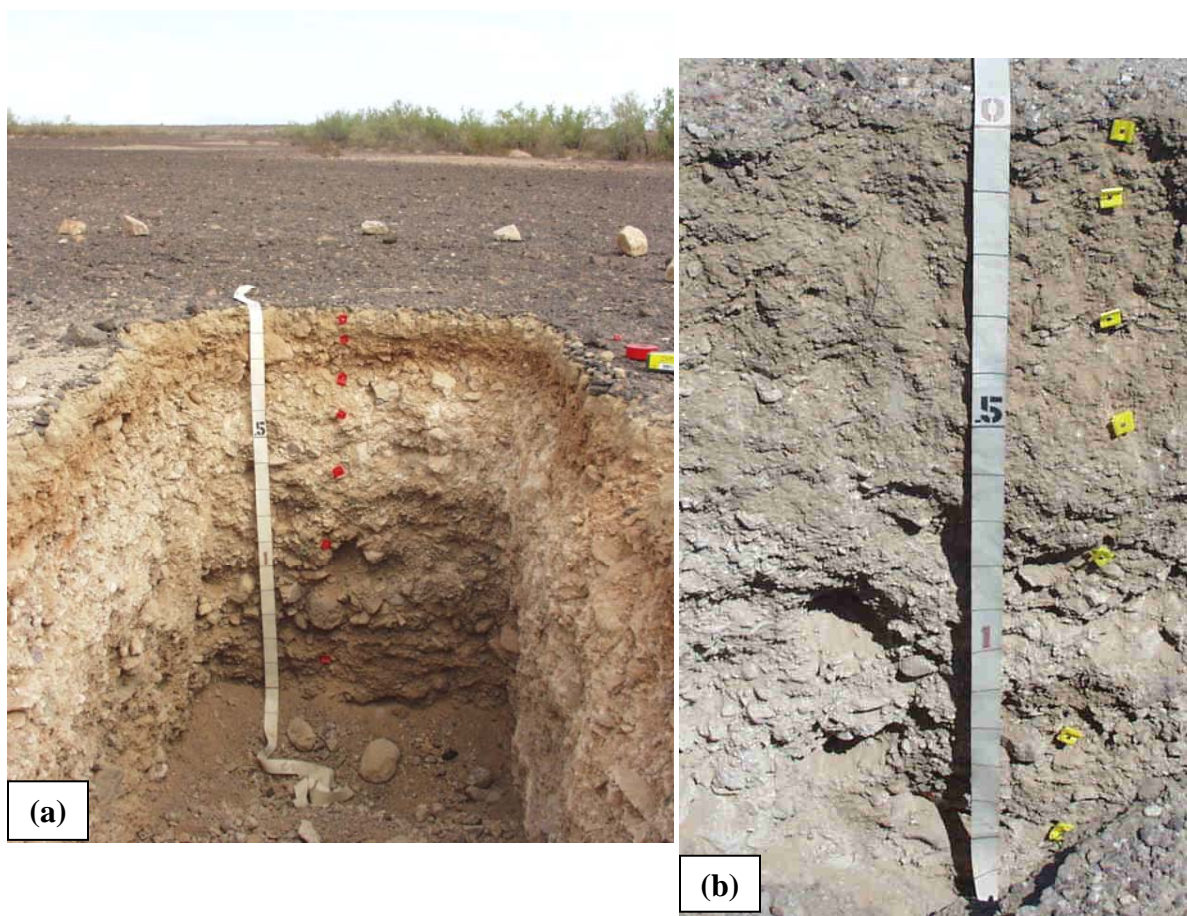


Figure 4.2.7. Photograph of a typical well-developed soil that underlies areas of pavement in interfluvial areas (a). The reddish color is due to accumulation of iron oxides and the white coloration is due to calcium carbonate and soluble salts. By comparison, a poorly developed soil that lies below first-order channels (b).

horizon are similar to desert pavements that are ubiquitous across the arid southwest U.S. (Bull, 1991; McFadden et al., 1998). The Av horizon overlies a well-oxidized B horizon with abundant accumulation of calcium carbonate. The top of soil C horizon starts at about 60–70 cm. Clasts shattered by salt weathering are scattered throughout the B horizon and upper C horizon.

Surfaces common to the first-order channels include imbricated gravels along the main channels, sand- to silt-rich bars within the channel, and silt-covered “floodplains” along channel margins (Fig. 4.2.7b). The soil underlying the lower reach of the first-order channels is poorly developed, consisting largely of the original alluvial fan sediment.

Depth profiles of particle-size distribution also display considerable differences (Fig. 4.2.8). Total silt plus clay content (particle size <0.062 mm) is highest in the Av horizon, ranging from about 73 to 68 percent weight, and decreases with depth. Several studies elsewhere in the southwestern U.S. have shown that the accumulation of this silt and clay is due largely to aerosolic dust, a common source of fine-grained material in desert soils (McFadden et al., 1987; McDonald, 1994; McFadden et al., 1998). By comparison, silt plus clay content in the sediment underlying the lower channel is

considerably lower, ranging below 50 percent weight. Silt and clay contents are slightly higher in alluvium underlying the upper channel and in the soils underlying the swales relative to the alluvium in the lower channel (Table 4.2.1). We interpret that high silt and clay content within the upper 50 cm in soils formed along the swales and upper channel is from the accumulation of soil from fluvial erosion and transport of soil from nearby plant scars.

Soluble salt content also varies considerably between soils underlying desert pavements and soils underlying channels. Soluble salt content increases to over 10,000 mg/kg (10% weight) within 50 cm of the surface underlying desert pavements. By comparison, salt content is < 500 mg/kg (<0.5% weight) for most layers within the upper 50 cm in sediment underlying channels. Soluble salt content only exceeds 1,000 mg/kg below a meter in sediment underlying the upper channel. Soluble salt content is also below 1000 mg/kg for soil underlying swales with the exception of one horizon with a soluble salt content of 2679 mg/kg. Depth profiles of soluble salt content for deep (>1.5 m) soil pits excavated into the desert pavement and upper and lower channel have similar, but more pronounced vertical trends (Fig. 4.2.9). Salt content is present in the soil underlying the upper and lower channel, and is substantially lower in concentration than the salt content of soils underlying the desert pavement.

INFILTRATION

Undisturbed Soil

Conductivity for soil surfaces that have a desert pavement and underlying Av horizon averages $1.72 \times 10^{-4} \pm 3.86 \times 10^{-5} \text{ cm sec}^{-1}$ ($0.6 \pm 0.1 \text{ cm hr}^{-1}$) (Table 4.2.2; Fig. 4.2.10). By comparison, the infiltration rates for subsoil underlying the Av horizon are considerably higher at $2.13 \times 10^{-2} \pm 1.03 \times 10^{-2} \text{ cm sec}^{-1}$ ($76.8 \pm 37.1 \text{ cm hr}^{-1}$). The subsoil measured is the Bwk or Bk horizon (Table 4.2.1). This large difference in conductivities occurs, in part, due to a strong capillary break existing between the Av and Bk horizon. The finer pore structure of the Av horizon will retain significant amounts of soil water in the near-surface before capillary pressures are enough to allow water to enter the larger pores of the Bk horizon.

Conductivity for soil at the swale, upper channel, and lower channel positions averages about four to six times greater than that of the Av horizon, with average values ranging from $6.46 \times 10^{-4} \pm 4.12 \times 10^{-4} \text{ cm sec}^{-1}$ ($2.3 \pm 1.5 \text{ cm hr}^{-1}$) for the upper channel to $9.86 \times 10^{-4} \pm 3.90 \times 10^{-4} \text{ cm sec}^{-1}$ ($3.6 \pm 1.4 \text{ cm hr}^{-1}$) for the lower channel.

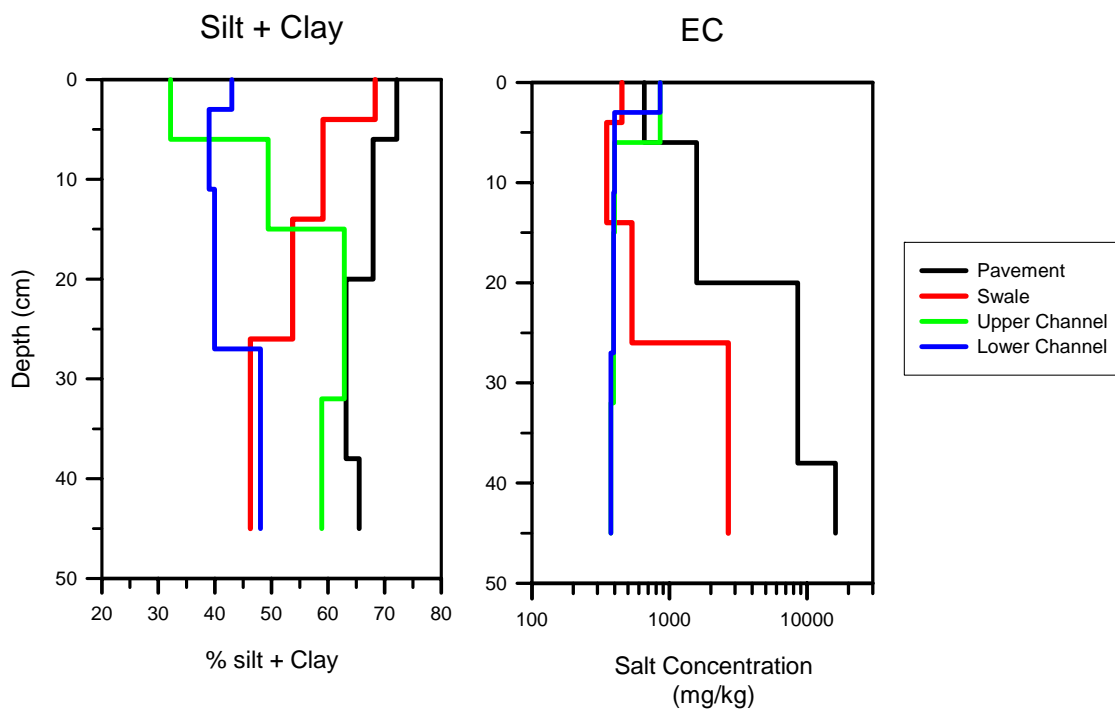
Soils Disturbed by Recent Vehicle Traffic or Military Activities

Infiltration was measured for desert pavement-covered soil surfaces that have been recently (< 3 years) disturbed by tracked or wheeled vehicles to compare with undisturbed soil surfaces (Table 4.2.2; Fig. 4.2.11). The level of disturbance varies from localized compaction and destruction of the pavement associated with vehicle tracks to complete removal of the desert pavement and the upper ca. 1–2 cm of the 4–6 cm thick Av horizon. The latter disturbance is associated with creation of a dirt access and training roads. Field observations indicate that under this level of disturbance the Av horizon is largely intact, especially overall morphology of the soil texture and structure.

Table 4.2.1. Summary of soil properties from soil TDR sites.

Position	Field ID	Horizon	Depth (cm)	% wt. Sand	% wt. Silt	% wt. Clay	EC	pH	CaCO3
Pavement	MWS1-1	Av	6	36	51	13	900	8.0	12.1
	MWS1-2	BAv	18	50	34	15	7794	7.9	8.9
	MWS1-3	Bwk	34	54	33	13	10714	7.9	5.5
	MWS1-4	Bk	50	73	21	6	11251	7.9	8.8
Swale	MWS2-1	Avk	6	34	56	10	360	7.7	6.6
	MWS2-2	Btk	20	32	41	27	320	7.7	6.4
	MWS2-3	Bk1	38	44	34	22	377	7.7	14.1
	MWS2-4	Bk2	45	48	39	13	183	7.7	24.1
Lower	MWS3-1	Avj	4	65	27	8	438	7.6	0.0
	MWS3-2	Ck1	8	68	22	10	282	7.5	2.7
	MWS3-3	Ck2	30	NS	NS	NS	NS	NS	NS
	MWS3-4	Ck3	48	55	27	17	649	7.6	16.8
Upper	MWS4-1		4	47	48	5	412	7.5	5.1
	MWS4-2		20	51	41	8	381	7.6	3.4
	MWS4-3		34	55	40	5	NS	7.6	7.1
	MWS4-4		54	58	32	10	620	7.7	17.4
Pavement	MWN1-1	Av	6	28	59	13	656	7.8	11.9
	MWN1-2	BAv	15	32	57	11	1577	7.8	15.5
	MWN1-3		28	37	48	15	8584	7.6	15.7
	MWN1-4		45	34	47	19	16102	7.4	19.5
Swale	MWN2-1		4	32	65	4	451	7.6	7.8
	MWN2-2		14	41	48	11	350	7.7	13.5
	MWN2-3		26	46	48	6	534	7.8	18.9
	MWN2-4		45	54	40	6	2679	7.7	24.3
Lower	MWN3-1	C1	6	68	28	4	855	7.6	5.1
	MWN3-2	C2	15	51	43	6	399	7.7	11.5
	MWN3-3	C3	32	37	47	16	393	7.7	27.2
	MWN3-4	Ck	45	41	44	15	376	7.8	21.6
Upper	MWN4-1		3	57	38	5	502	7.7	4.5
	MWN4-2		11	61	31	8	283	7.7	2.6
	MWN4-3		27	60	31	9	311	7.7	7.7
	MWN4-4		45	52	35	13	365	7.7	13.4

North Drainage



South Drainage

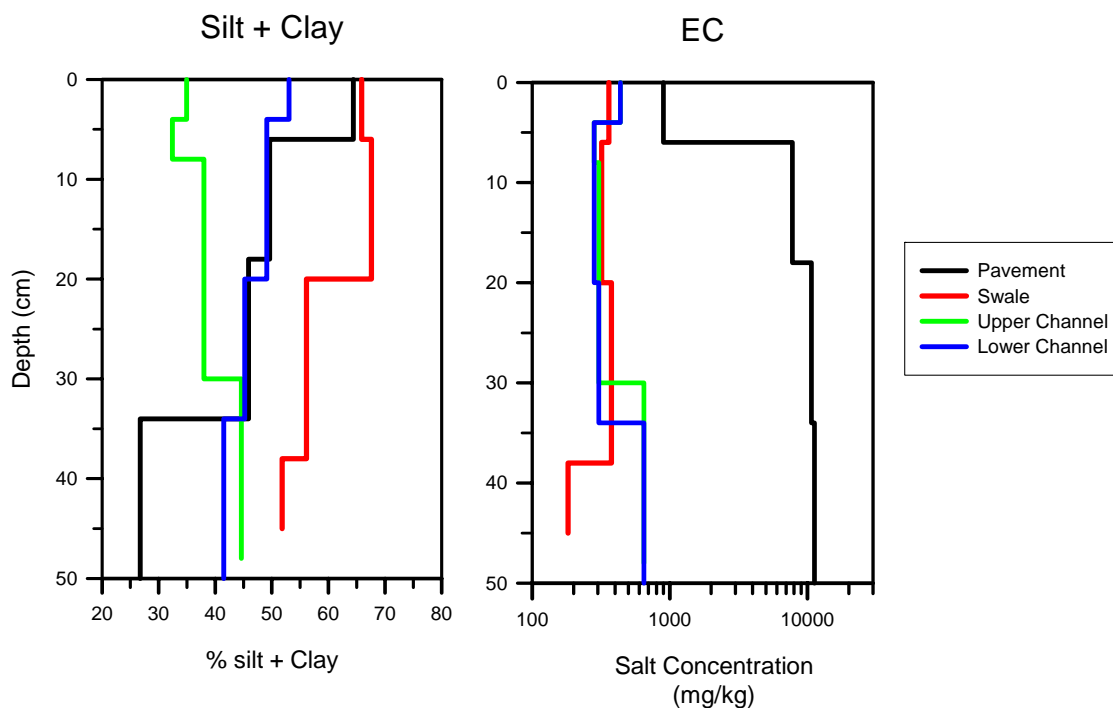


Figure 4.2.8. Depth profiles of soils at each of the four TDR probe locations in the north and south drainage sites. Note log scale for depth profiles of soluble salts (EC).

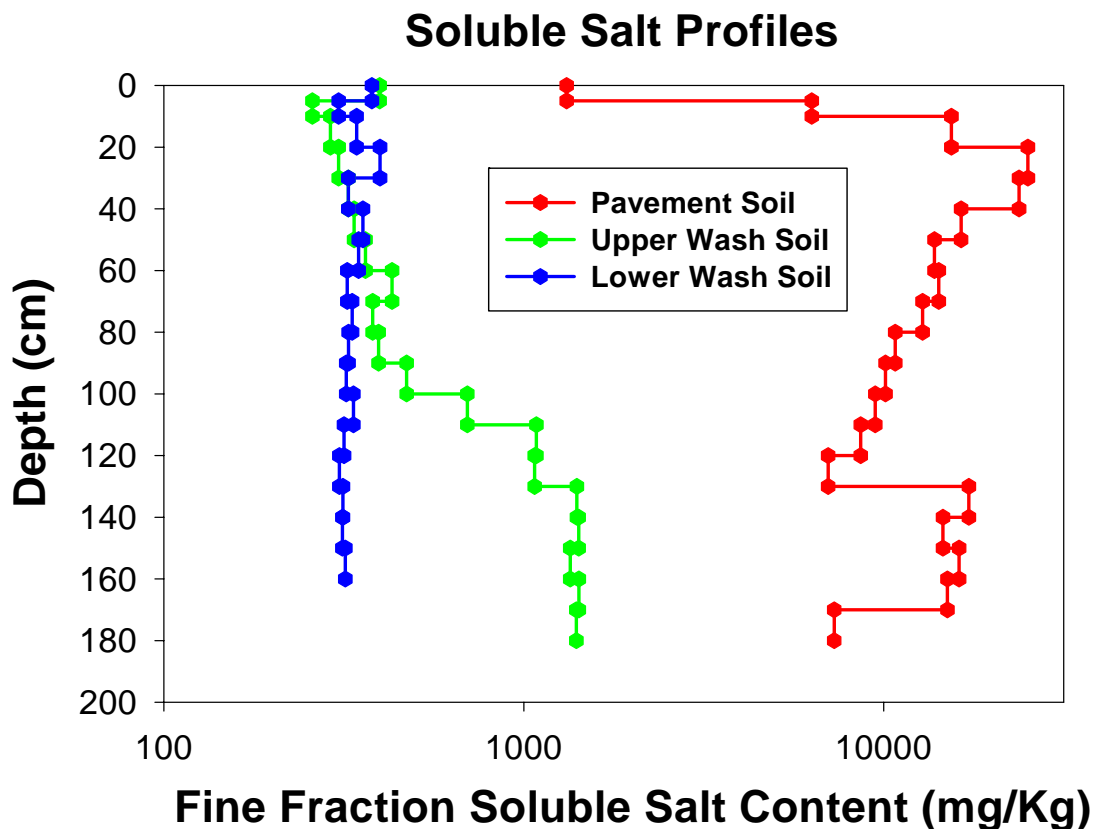


Figure. 4.2.9. Depth profiles of soluble salt content for deep soil pits excavated into the desert pavement, and upper and lower channels. Salt content below the pavement (note log scale on x-axis) is considerably greater than salt content in channel soils.

Infiltration was measured at $1.42 \times 10^{-4} \text{ cm sec}^{-1}$ (0.5 cm hr^{-1}) on a previously undisturbed Av horizon after two passes by a $5.4 \times 10^7 \text{ kg}$ drill rig (ten wheels). Average conductivity was measured at $1.09 \times 10^{-4} \pm 6.69 \times 10^{-5} \text{ cm sec}^{-1}$ ($0.4 \pm 0.2 \text{ cm hr}^{-1}$) for a disturbed Av horizon along a three-year-old vehicle path (approximately 30–50 passes by four-wheeled vehicles). Two transects consisting of five infiltration measurements were conducted across three-year-old vehicle path to further test the spatial variability of impacts to the desert pavement (Fig. 4.2.12). Results show that infiltration is generally slightly reduced below tracks relative to the infiltration for undisturbed soil adjacent to each track.

Soils Disturbed by Historic Military Activities

Infiltration was also measured for disturbed desert pavement at what is interpreted to be circa 1942 training site associated with General G. S. Patton's U.S. Army Desert Training Center. Disturbance consisted of both relict armored vehicle tracks, preserved due to severe compaction and destruction of the pavement, and tent bivouac sites created by scraping away the desert pavement and the upper 1-2 cm of the of the 4-6 cm thick Av horizon. Infiltration for a distinct, but relict track scar (Sherman

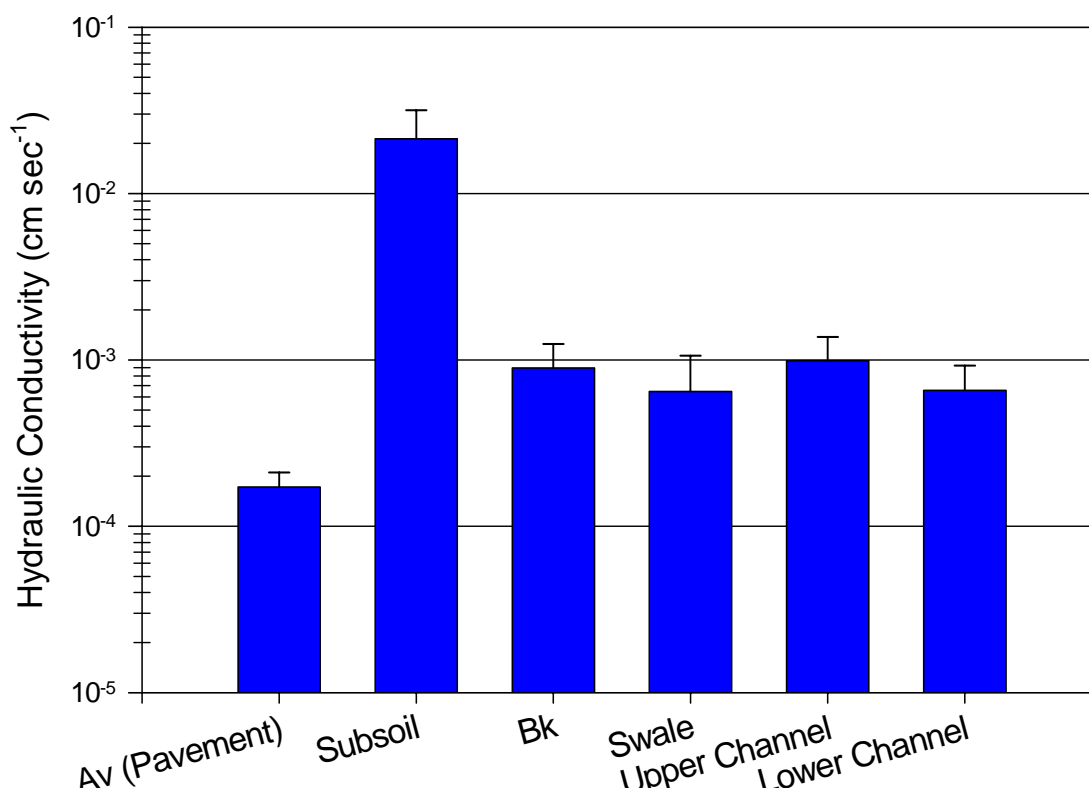


Figure 4.2.10. Variation in average infiltration rates across key surfaces and subsoil horizons. Av horizons have the lowest infiltration rate whereas the underlying Bw horizon has the highest rate of infiltration. Brackets denote one standard sigma deviation. Infiltration measured using a disc permeameter.

Table 4.2.2. Summary of infiltration results.

Soil Disturbance	Horizon or Feature	n	K(h) cm sec-1		K(h) cm hr-1	
			Mean	Stdev	Mean	Stdev
Undisturbed	Av (pavement)	11	1.72E-04	3.86E-05	0.6	0.1
Undisturbed	Subsoil	3	2.13E-02	1.03E-02	76.8	37.1
Undisturbed	Swale	3	8.94E-04	3.52E-04	3.2	1.3
Undisturbed	Upper Channel		6.46E-04	4.12E-04	2.3	1.5
Undisturbed	Lower Channel	4	9.86E-04	3.90E-04	3.6	1.4
Recent	Drill Rig Scar	1	1.42E-04		0.5	
Active	Wheel Track	5	1.09E-04	6.69E-05	0.4	0.2
Old	Patton Tank Track	1	1.55E-04		0.6	
Old	Tent site	1	9.83E-05		0.4	
Old	Scraped Av	1	1.92E-04		0.7	
Old	Old Scar Av	1	1.29E-04		0.5	

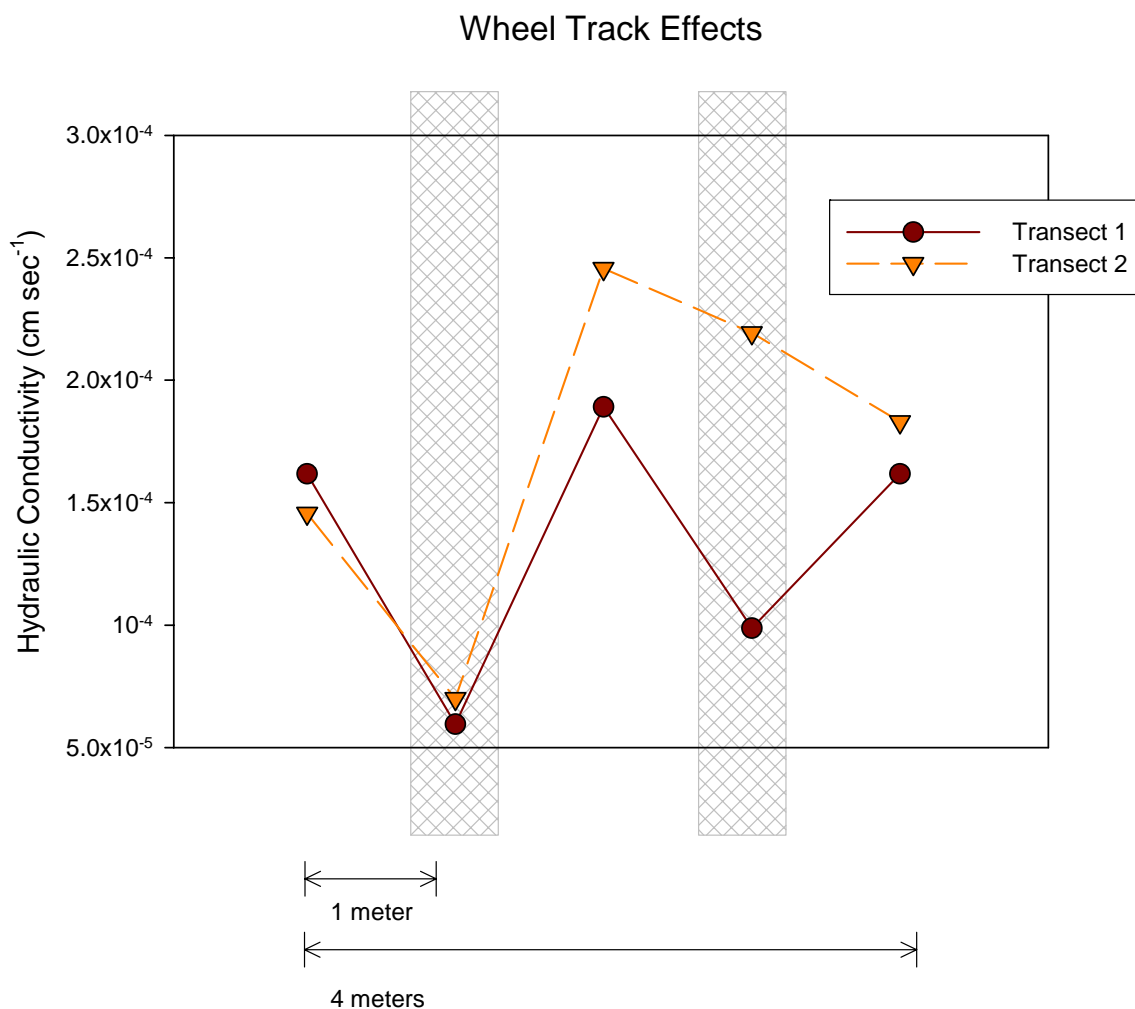


Figure 4.2.11. Changes in measured infiltration rate as superimposed across a diagram of wheeled vehicle tracks (hatch pattern). Vertical axis is infiltration rate and horizontal axis is approximate transect distance.

tank?) was measured at $1.55 \times 10^{-4} \text{ cm sec}^{-1}$ (0.6 cm hr^{-1}). Observations of the Av soil morphology indicate that the soil structure has partially reformed since the disturbance due to soil dispersive stress associated with episodic wetting and drying. An infiltration rate of $9.863 \times 10^{-5} \text{ cm sec}^{-1}$ (0.4 cm hr^{-1}) was measured on the relict tent bivouac sites. Infiltration was also measured on a highly disturbed desert pavement mechanically scraped during construction of the main access road into the Cibola site, removing about 2-3 cm of the original. The post-disturbance infiltration rate was likely to be lower because re-establishment of the soil structure will increase infiltration. We also measured a surface where the desert pavement had been scraped away to form pads for tents. These tent sites are in the same area as the tank track above and also appear to date from about 1942. An infiltration rate of $9.863 \times 10^{-5} \text{ cm sec}^{-1}$ (0.4 cm hr^{-1}) was measured on the old tent sites. Infiltration was also measured on a highly disturbed desert pavement, mechanically scraped during construction of the main access road into the YPG study area from Cibola site Av horizon. The disturbance appears to be about 30 to 50 years old. The infiltration rate for the scraped surface is $1.92 \times 10^{-4} \text{ cm sec}^{-1}$ (0.7 cm hr^{-1}).

RUNOFF EVENTS AND CHANNEL FLOW

Two channel runoff events were recorded between January 2000 and December 2001. One runoff event occurred on August 27, 2000 following a large convective storm (Fig. 4.2.12). This storm delivered 34.6 mm, with most of the rainfall occurring in a 5-10 minute period (based on local rain gauge; 16.2 mm recorded at Blythe). Channel flow reached in maximum height of 20-30 cm within



Figure 4.2.12. Photograph of typical channel morphology of gravel and silty-sandy bars along first-order channels. Photograph is of north drainage channel (N1) following large a runoff event on August 27, 2000.

the lower reach of N1 and S3 channels as recorded by flow lines on vegetation, channel scour marks, and sediments and debris deposited by the flow (Fig. 4.2.12). Channel flow during this event obtained approximately 30-50% of maximum (bank-full) channel flow based on visual estimates of the total channel area.

A second channel flow event occurred March 5-6, 2001 during a large Pacific frontal storm. This storm delivered 0.25 mm on March 5, with another 38.6 mm occurring on March 6. Field observations of channel scour marks, and sediment and debris deposited by the flow indicate that the

channel flow reached a maximum height of only about 5-10 cm, and that this flow was primarily constricted to the deepest channel rills. Channel flow during this event obtained approximately 5-10% of maximum (bank-full) channel flow based on visual estimates of the total channel area.

Evaluation of the Blythe precipitation record between July 1996 and May 2002 suggests that at least two runoff events have occurred in 1997 and 1998 (Fig. 4.2.13). The largest runoff event since 1996 must have been associated with tropical storm Nora, which occurred in September 24-25, 1997. A total of 51.5 mm of rainfall was recorded at Blythe over a two-day period (48.3 mm on day 2). Most of the ephemeral channels, including many first-order channels, were flowing at full capacity (bank-full) for several hours according to YPG personnel who witnessed this storm. Field observations of channels in the study area of this project have identified a wide variety of flotsam along channels that preserve a record of bank-full discharge, especially along channels N1 and S3. This flotsam, first observed in February 2000, was largely in place and without signs of long-term exposure to the elements, indicating that the most likely source was runoff associated with tropical storm Nora. A second runoff event is likely to have occurred in conjunction with a frontal storm on February 3, 1998. This storm delivered 34.5 mm and is likely to have generated limited runoff. If runoff did occur, the volume would have been similar to the frontal storm of 38.6 mm of March 6, 2001, which also exceeded 30 mm of precipitation. Two frontal storms, February 17 with 24.1 mm and March 17 with 26.4 mm, may have produced runoff into the first-order channels. Any channel flow generated during these two storms, however, was likely limited to the deepest channel rills.

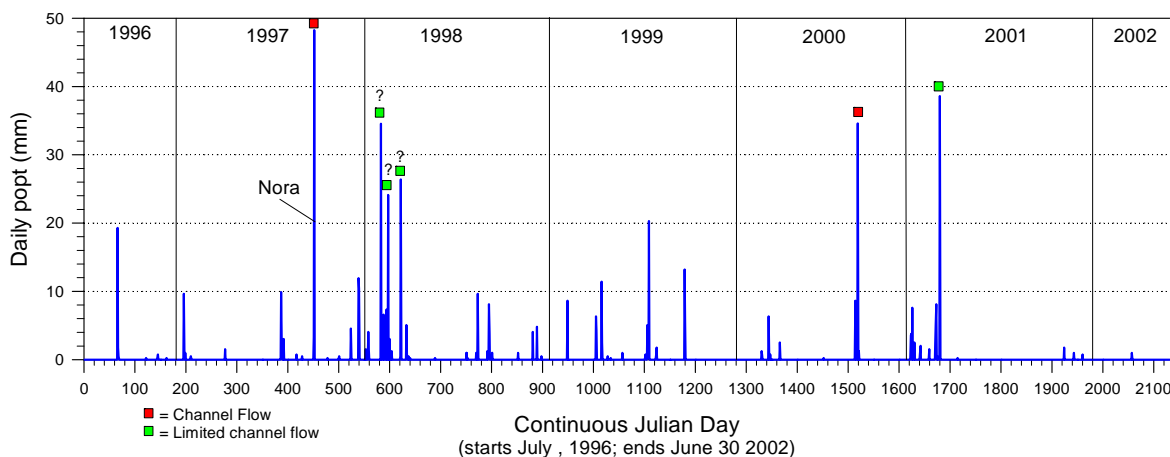


Figure 4.2.13. Daily precipitation measured at the Blythe airport (~ 20 km north of study site) for the period from July 1, 1996, to June 30, 2002. Large precipitation event (~Julian day 445) is due to Tropical Cyclone Nora, September 1997.

Field observations of the desert pavement, channels, and our runoff plots indicate that very limited runoff was produced during several intervals of precipitation during 2001-2002 but was not sufficient to produce channel flow. Surface runoff appears to have only flowed across the pavement for only a few meters and that the surface flow was not sufficient to reach the channel.

TEMPORAL TRENDS IN SOIL MOISTURE

Results indicate that baseline conditions for soil moisture ranged from 4–8% for all soil layers. An example baseline conditions is July 18, 2000 (Table 4.2.3). The soil during this part of the year represents the driest soil conditions due to prolonged high temperatures and a lack of preceding rainfall (May and June are commonly the driest months during the year). Baseline conditions were also established by November 2000 and September 2001 following periods without additional precipitation and high summer to fall temperatures.

Table 4.2.3. Volumetric soil moisture for all sites.

North Site			3/9/2000	3/16/2000	7/18/2000	9/4/2000	9/14/2000	10/8/2000	11/6/2000	3/18/2001	9/6/2001
Pavement	MWN-1	5cm	8.6	7.3	5.8	11.9	8.3	7.2	7.7	17.2	6.9
Pavement	MWN-1	26cm	7.4	8	7.6	7.5	9	9	7.6	15.6	9.6
Swale	MWN-2	5cm	5.8	5.5	4.5	7.7	5.2	4.9	5.2	10.1	4.4
Swale	MWN-2	26cm	5.9	6.2	5.9	6	6.4	4.2	5.9	13.7	5.7
Upper Channel	MWN-3	5cm	5.8	4.7	5.1	13.3	7.4	5.2	5.6	12.7	5
Upper Channel	MWN-3	26cm	6.4	6.3	6.3	22	10.2	9.8	7.7	23.4	7.9
Lower Channel	MWN-4	5cm	5.1	5.5	4.6	10.7	5.8	4.3	5.6	10.2	5.2
Lower Channel	MWN-4	29cm	6.1	6.7	6.4	15.3	11.1	9.7	8.9	15.4	9.7
South Site											
Pavement	MWS-1	5cm	6.1	6.1	5.3	15.5	8.4	6.8	7.6	15.7	6.7
Pavement	MWS-1	26cm	6	6.6	6	5.7	6.7	7.2	6.4	10.2	6.9
Swale	MWS-2	5cm	11.8	7	7.2	19.7	13.2	8.8	9.8	21.6	9.4
Swale	MWS-2	26cm	6.7	11	6.1	6.2	6.7	6.9	6.4	19.9	6.4
Upper Channel	MWS-3	5cm	5.3	4.6	4.1	9	5.1	4.2	4.7	8.3	4.4
Upper Channel	MWS-3	29cm	6.3	6.9	6.8	22.5	16	7.4	9	18.9	9.7
Lower Channel	MWS-4	5cm	5.3	4.6	4.2	9.2	4.9	4.3	4.6	10.8	4.2
Lower Channel	MWS-4	28cm	6.9	6.7	6.3	8.9	8	9.7	6.8	18.5	7.4

Infrequent storms with daily precipitation less than 10 mm have limited impact on soil moisture. Soil moisture recorded at March 9, 2000 shows only slightly elevated levels of soil moisture (relative to July 2000 baseline) although 9 mm of rainfall had occurred during the previous two weeks, including 6 mm of rainfall that occurred two days before measurement of soil moisture. A series of frontal storms over a five-day period between February 25 and March 1, 2001 provided 16 mm of rainfall, with a daily maximum of 8 mm. Soil moisture readings were not conducted during this period, but field observations during excavations of additional soil pits indicated that the soils were dry with little apparent soil moisture.

The largest increases in soil moisture are associated with storms that produce channel runoff events. Measurements of soil moisture after two runoff events that occurred on August 27, 2000 and March 6, 2001 record considerable increases in soil moisture (Fig. 4.2.14). The largest relative increases in

volumetric moisture are associated with the channel soils, especially the lower soil at about 30 cm in both the N1 and S3 drainages (Table 4.2.3). This increase is in response to infiltration of soil water along each channel during runoff events. The soil below the pavements had the largest increase in soil moisture after the frontal storm in March 2001. Soil moisture dropped to near baseline levels within one month following infiltration resulting from the August 27, 2000 storm.

ELECTROMAGNETIC (EM) INDUCTION

One of the objectives of this project was to test new technology that can enhance land managers' abilities to quickly and effectively monitor soil moisture over large areas. We tested the potential application of surface measurements of bulk soil electrical conductivity to determine if conductivity measured by the EM-38 could be correlated with observed trends in soil moisture in the north and south drainages. The efficacy of using bulk soil electrical conductivity measured by electromagnetic induction as a means of determining soil water content has been shown by several investigators (Rhoades et al., 1976, Kachanoski et al., 1988, Hendrickx et al., 1992). Kachanoski et al. (1988) determined that spatial variations of soil water content correlate well with changes in soil electrical conductivity. In an additional study, Kachanoski et al. (1990) found that 80% of the variation in water content is explained by changes in soil electrical conductivity. These two studies, however, were conducted in environments of low concentrations of dissolved electrolytes in the soil. Arid soils high in salt content, like those at YPG, complicate the interpretation of EM data by introducing another dependent variable of dissolved electrolytes. Electrical conductivities are no longer primarily a function of moisture content, but are also influenced by the locally high levels of soluble salts in the soils.

Most of the EM data exhibit expected trends (Fig. 4.2.15). Measurements taken in the deeper (1.5m) sensing vertical dipole mode are all higher than those taken in the horizontal mode. This is most likely due to the translocation of aerosolic salts to deeper depths during precipitation events. The data from all transects also show a decrease in conductivity near the wash. First order drainages, such as the one from which the data were collected, are catchments for any runoff that occurs over a given area. Runoff is concentrated in these washes; consequently, the soils in the channels are better drained than those underlying pavement. However, downstream transects show no noticeable decrease in conductivities.

Nearly all transects from each sampling period display an anomalous conductivity spike on the southern edge of the channel. As the survey moves onto the southern pavement surface out of the wash, conductivities taper off to values that are slightly higher than those on the northern pavement. However, a geomorphic explanation for this recurrent conductivity spike, that a greater percentage of fines is deposited due to properties of the channel itself, is not consistent with the particle size analysis. The most probable reason for the increase in conductivity is a higher concentration of salts on the southern slope. The mechanism by which this increase occurs is not clear, although it is likely hydrologic in origin. The minimal distance between the edges of the wash does not provide evidence to indicate that the higher conductivity on the south side is geologic in origin. Furthermore, the aspect of the slopes is very slight and thus probably not the result of a higher evaporation rate due to differences in sun exposure on the southern edge. Additional data collection would be necessary to adequately explain this anomaly.

The results of these EM surveys indicate that the EM-38 has potential as a soil moisture sensor; however, differentiation between a poorly drained area of high salt content and zones of increased moisture is difficult. In salt-affected soils, EM surveys should be supplemented by independent measures of soil moisture with which to compare the EM data. If supplementary data exists, this method can provide valuable qualitative data about the spatial variation of soil moisture.

PLANT RESPONSE

Of the three species, creosotebush showed the greatest degree of variation in predawn water potential (ψ_{pd} ; Fig. 4.2.16). Ironwood and paloverde did not change in ψ_{pd} across surfaces or between drainage locations, but they did show significant changes in ψ_{pd} through time (Table 4.2.5). In both cases, these changes were due to marked increases in ψ_{pd} immediately following channel flow during the storm on August 27, 2000 (Figs. 4.2.14; 4.2.16). Following the other non-runoff-generating storms in 2001, ψ_{pd} in ironwood and paloverde did increase compared to low values prior to and after the run-on event (Fig. 4.2.16), but it did not achieve the levels apparent immediately following the latter storm. In marked contrast to these deep-rooted species, creosotebush showed a significant difference between upper and lower drainages pooled across both surfaces (-5.7 MPa and -5.4 MPa, respectively), as well as a significant surface-by-time interaction (Table 4.2.4). The differences between drainage locations are very small and probably not biologically significant and more likely reflect large sample sizes. Prior to the large August 2000 channel flow event, creosotebush did not show any consistent difference between north and south drainages. During the dry-down period following the run-on event, plants growing on the north surface diverged to higher ψ_{pd} levels compared to south surface counterparts. However, following the two non run-on-producing storms of 2001, ψ_{pd} in southern drainage plants became significantly higher compared to those in north surface plants. These contrasting seasonal patterns resulted in the significant two-way interaction.

Table 4.2.4. Individual ANOVA F-test results of seasonal predawn water potential responses of desert ironwood, foothills paloverde and creosotebush growing on two differently aged geomorphic surfaces and at upper and lower first-order drainage locations from April 2000 to September 2001.

Effect	Ironwood	Paloverde	Creosotebush	Df
Surface (Sur)	0.06	1.53	0.86	1, 4
Location (Loc)	0.04	2.16	5.29**	1, 76
Date (D)	39.75***	46.11***	148.61***	9, 76
Sur x Loc	1.20	1.98	0.43	1, 76
Sur x D	0.79	0.92	3.87***	9, 76
Loc x D	0.44	0.88	0.46	9, 76
Sur x Loc x D	0.36	0.86	1.08	9, 76

P < 0.05; *P < 0.01

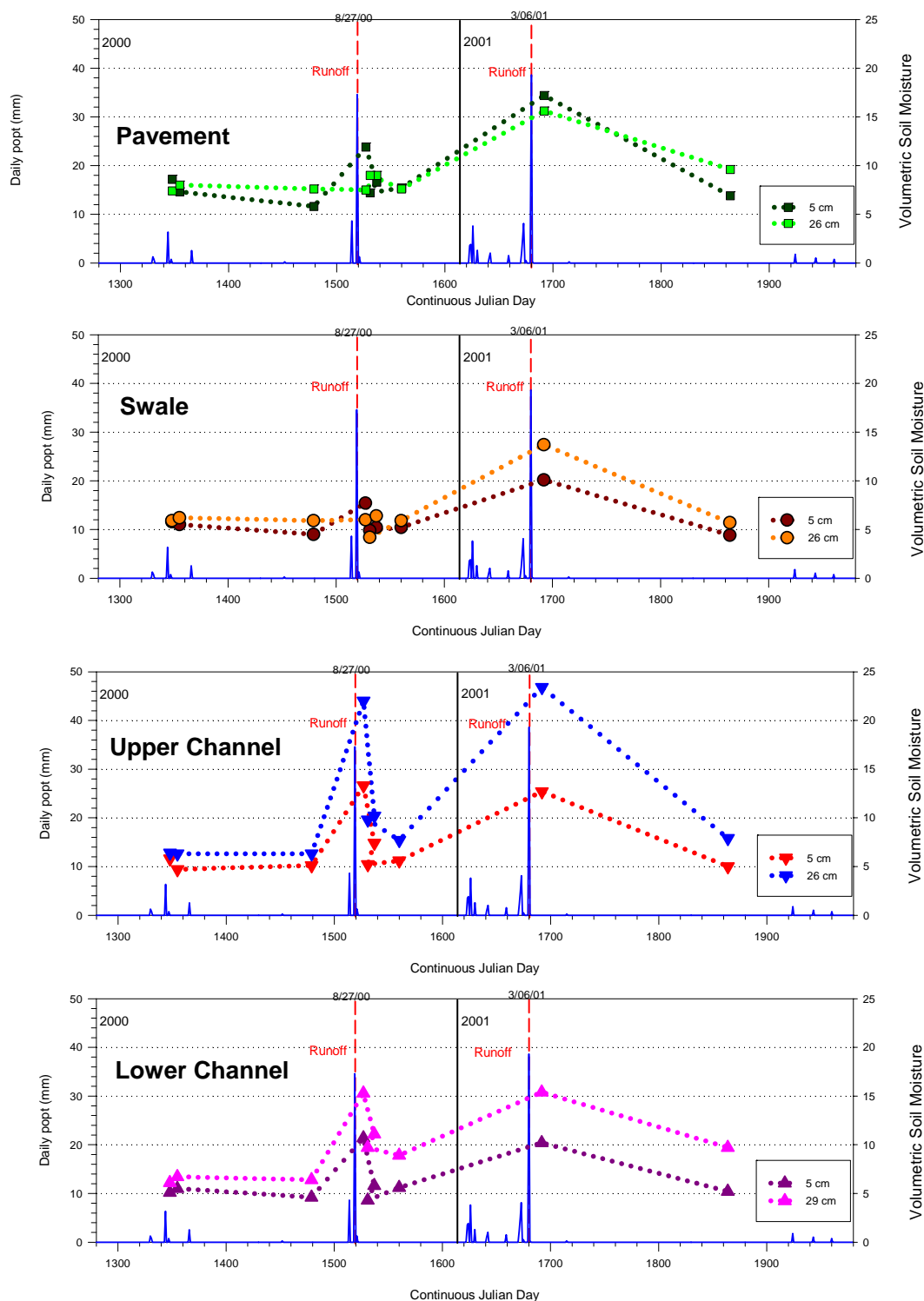


Figure 4.2.14. Comparison among precipitation, episodes of surface runoff and channel flow, and volumetric soil moisture for the north drainage site. Results for the south drainage site are similar.

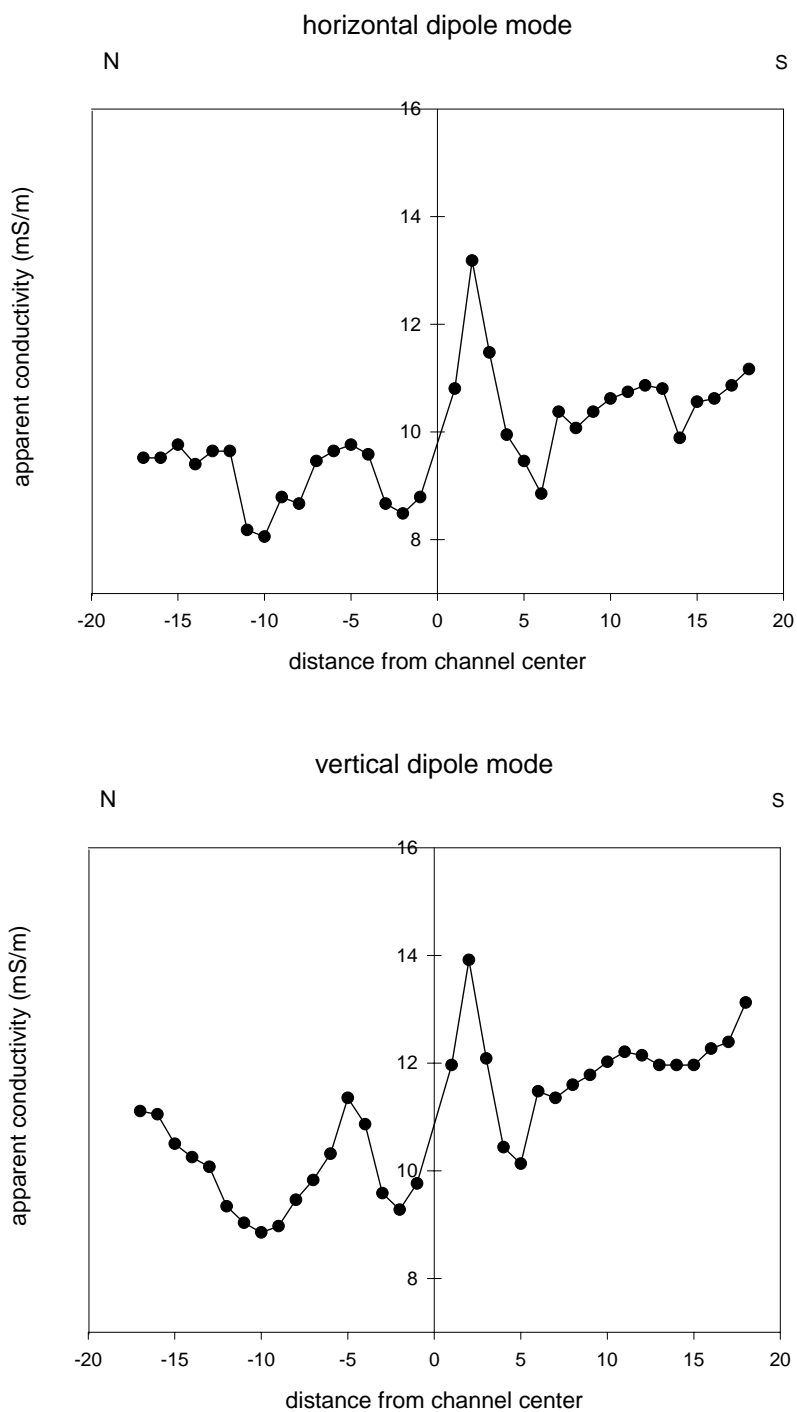


Figure 4.2.15. Results of EM 38 data transect data across the N1 channel. Dots represent individual readings along a transect from N to S and shows point where transect crosses the middle of the first-order channel. All transects in the N1 and S3 drainage basin recorded similar EM 38 results.

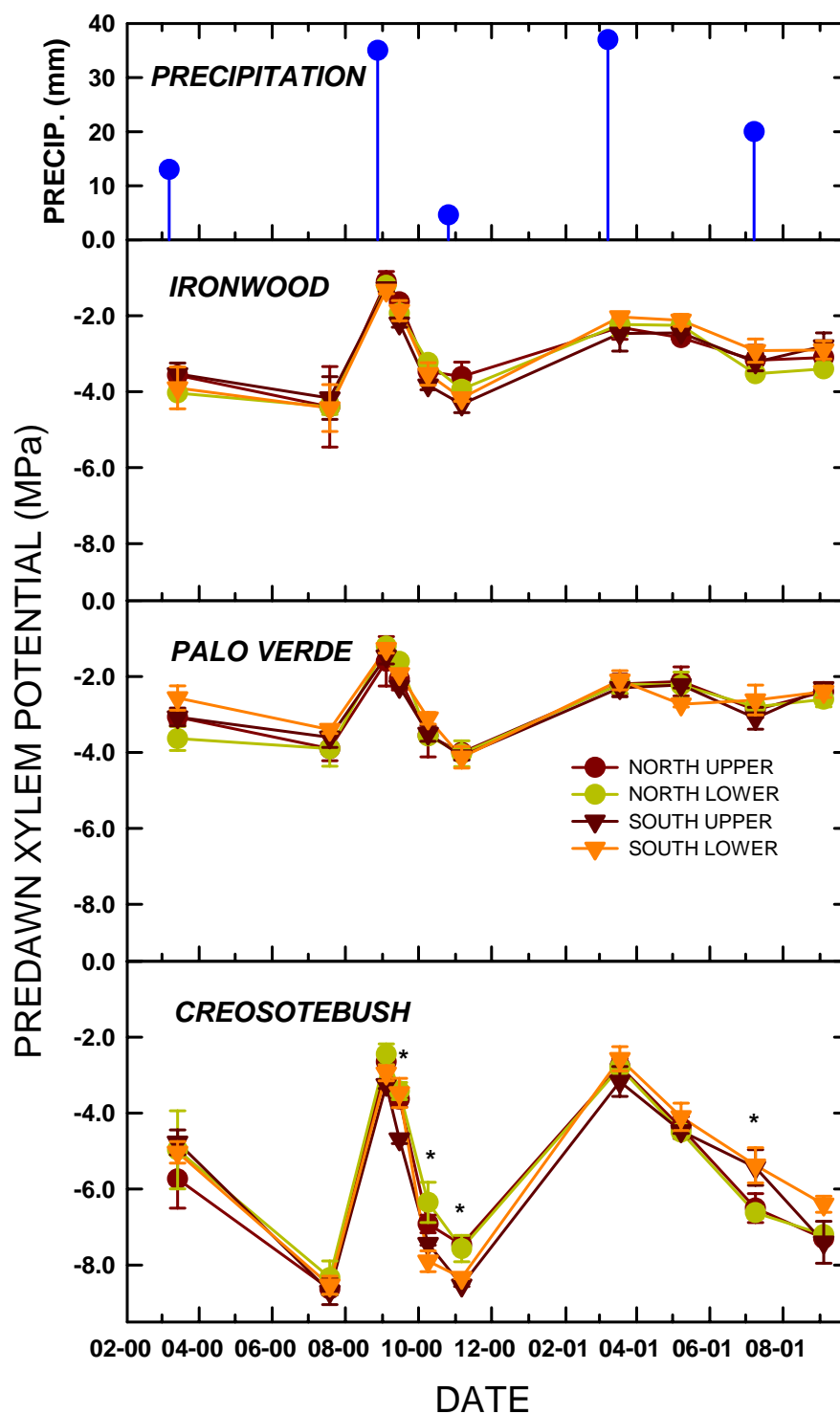


Fig. 4.2.16. Seasonal precipitation and predawn water potential of desert ironwood, foothills paloverde and creosotebush growing in upper and lower first-order drainage positions on two distinct geomorphic surfaces on the YPG, Arizona, U.S. for the years 2000 and 2001. Each point is the mean of three independent measurements. Bars indicate \pm one standard error. The * indicates significant surface differences within that sampling date (t-test on ANOVA results).

DISCUSSION

Soil Characteristics

Development of key soil properties

Soil characterization results demonstrate the strong contrast in properties between the soils common to the first-order channels and soils underlying the surrounding desert pavement. The desert pavement soils have a considerable accumulation of aerosolic dust, resulting in a soil that has high contents of silt and clay in the uppermost soil horizons. The Av horizons commonly have the highest amount of silt and clay relative to underlying horizons or to soils that lack Av horizons. The characteristics of desert pavement soils are typical for soils formed on alluvial fans and alluvial terraces that are ubiquitous across the arid regions of the southwest U.S. Several studies elsewhere in the southwestern U.S. have shown that the source of this silt and clay is predominantly from the accumulation aerosolic dust, a common source of fine-grained material in desert soils (Birkeland, 1999). Moreover, the accumulation of aerosolic dust is a primary driver in the formation of desert pavements (McFadden et al., 1987; McDonald, 1994; McFadden et al., 1998). The dust is also the predominant source of soil carbonate and more soluble salts.

Another important aspect of the desert pavement is that the formation requires several millennia of a stable soil surface, especially a lack of faunal and flora mixing at the soil surface (Bull, 1991; McDonald, 1994; McFadden et al., 1998). This indicates that the areas of desert pavement are not conducive to the establishment of most desert plants. In other words, the formation of a desert pavement is likely to restrict establishment of desert plants.

The soils formed along the small tributary swales, and the upper 40-50 cm of the upper and lower channel soils also have a high content of silt and clay. We interpret that high silt and clay content within the upper 50 cm in soils formed along the swales and upper channel is from the accumulation of soil from fluvial erosion and transport of soil from nearby plant scars.

Infiltration rate for disturbed and undisturbed soils

An average infiltration rate of less than 1 cm hr^{-1} measured is similar to infiltration rates measured for other desert pavements and Av horizons (McDonald, 1994, 2002; McDonald et al., 1996). This low infiltration rate indicates that areas of desert pavement are conducive to generating surface runoff into adjacent channels during larger convective or frontal storms. Infiltration rates of less than 1 cm hr^{-1} were also measured for disturbed soils indicating that compaction of the desert pavement and Av horizon and removing the upper few centimeters of Av horizon will have a limited impact on infiltration. Lack of any real change in infiltration indicates the capacity of these soils to generate surface runoff is likely maintained under limited surface disturbance.

There are two reasons for the low infiltration rate, even for soils with disturbed, but partially remaining Av horizons. One reason is that the high silt and clay contents remains after limited disturbance (i.e. compaction, shallow scraping) disturbance. The rate of infiltration into soils will largely decrease with increasing silt and clay content (Kutilek and Neilson, 1994). A second, and perhaps more important, reason the infiltration rate is not altered under limited disturbance is that the overall morphologic character of the Av horizon is maintained. Detailed evaluation of Av horizon

indicates the platy soil structure and abundant vesicular pores that are common to Av horizons have a strong control on the conductivity of the Av horizon (Young et al., 2004). This structure is clearly modified under compaction and minor scraping of the desert pavement, while the basic character of the structure remains.

By comparison, infiltration rate is considerably higher for soils horizons that lie below the Av horizon. A high infiltration rate $\sim 77 \text{ cm hr}^{-1}$ for the underlying B horizon indicates that complete removal of the Av will result in a profound decrease in surface runoff. The profound difference in infiltration is largely in response to a silt and clay content that is lower than the overlying Av horizon, but also because the B horizons commonly lack the platy soil structure and abundant vesicular pores, morphologic properties that tend to decrease hydraulic conductivity.

Infiltration into the channel soils and small adjoining swales, ranging about $2\text{--}3 \text{ cm hr}^{-1}$, is only three times the rate of the desert pavement. This rate is lower than expected for channel soils, but is consistent with the high silt content of the soils formed along the swales. Silt and clay content in channel soils, although lower than that of the swales and desert pavement soils, exceeds nearly 40% by weight, which is of sufficient abundance to limit infiltration relative to gravel rich channels sediments. Infiltration along the deepest channel rills, which are lower in silt and clay content relative to the main channel areas, would likely have a higher rate of infiltration.

RUNOFF AND CHANNEL FLOW

An important finding of this study is the limited occurrence of surface run-off of sufficient magnitude to create channel-flow. Field observations indicate that although storms may occasionally produce limited, localized runoff, storms that have the precipitation of adequate intensity or duration to produce channel flow are very infrequent. Field observations and evaluation of weather data indicate that only four channel flow events are likely to have occurred between 1996 and 2002 (Fig. 4.2.13). The volume of three of the flows was less than 50% of the maximum channel volume and one, a rare tropical storm, equaled maximum channel volume. This relation suggests that channel flow and volume is highly episodic and only occasionally of high volume.

SOIL MOISTURE

Results of soil moisture monitoring indicate that precipitation rarely infiltrates below the Av horizon and into the underlying soil. Increases in soil moisture that exceeded at least 5% volumetric moisture content only occurred after a large frontal storm that delivered 38 mm of precipitation (Fig. 4.2.13; Table 4.2.3). Studies of infiltration have shown that precipitation from large, slow-moving frontal storms is required to provide sufficient water to penetrate below the Av horizon (McDonald, 1994, 2002; McDonald et al., 1996). Likewise, precipitation that did not produce surface runoff into the channels also did not yield increases in soil moisture that exceeded at least 5% volumetric moisture content for soil in the upper or lower channel (Fig. 4.2.13; Table 4.2.3). Precipitation that does not penetrate the Av (i.e. infiltration exceeding $\sim 6 \text{ cm}$ into the underlying soil) horizon or generate surface runoff will be quickly lost to evaporation. Most precipitation in this arid environment, therefore, is likely to be lost from evaporation from the soils covered by desert pavements. Considerable increases in soil moisture content, especially at nearly 30 cm depth, only coincided with channel flow that occurred August 2000 and March 2001. This indicates that channel flow is probably required to provide sufficient water to increase soil moisture in soils along the channel.

Depth profiles of soluble salt content further demonstrate the importance of channel flow on supplying soil moisture to the channels (Fig. 4.2.9). Soluble salts are easily dissolved and transported by percolating water during infiltration. The highest soil salt contents are associated with the desert pavements where infiltration and downward translocation of soil moisture is insufficient to leach salts from the soil profile. By comparison, depth profiles for channel soils show the opposite trend. Salt contents are lowest for the lower channel soil indicating that the downward flux of soil moisture is sufficient to prevent the build up of salts at least to 1.5 m. The salt content steadily increases at about 1 m in the upper channel soil indicating that the downward flux of percolating water is less than that of the lower channel, but considerably higher than that of the desert pavement. The relative differences in salt content between the upper and lower channel positions is consistent given the that the lower channel will nearly always receive a greater flux of water from channel flow relative to the upper channel position. A critical aspect of the depth profiles is that although surface flow is episodic and likely occurs less than once a year, the long term trend is that downward percolation of soil moisture is at least great enough to prevent the accumulation of soluble salts. In other words, soil and geomorphic relations indicate that surface runoff and channel flow occur frequently enough to be a dominant source of water that percolates into the soils underlying the channels.

PLANT RESPONSE

The predawn water potential responses show that these species responded to different determinants of soil hydrology. Deep-rooted ironwood and paloverde showed marked increases in ψ_{pd} only following the single, large run-on-producing storm, even though this event did not generate more rainfall than either of the non-flow-generating events (Figs. 4.2.13 and 4.2.16). This first suggests that, on these surfaces and drainage locations, neither of these species utilized saturated zone water and were not operating as phreatophytes. These results also strongly suggest that only storms producing significant amounts of run-on are capable of recharging to the deep soil depths that ironwood and paloverde use. In both species, ψ_{pd} did increase following the 2001 rainfall events, suggesting that both have shallower, likely more laterally-distributed, roots capable of using more transient forms of water inputs (Smith et al., 1997). Thus, ironwood and paloverde are responsive not only to how the surrounding pavement-covered drainage area delivers augmentation, but also to the effectiveness of the properties of the soil within the drainage channel itself as it affects rainfall inputs.

Channel soil effects become all the more apparent in creosotebush, which showed significant seasonally varying responses between north and south surfaces as well as to drainage location (Fig. 4.2.16). Indeed, unlike ironwood and paloverde, ψ_{pd} in creosotebush immediately following the 2001 storms was significantly indistinguishable from levels attained following the 2000 run-on event (Fig. 4.2.16). In creosotebush, therefore, soil properties in the drainage channel are of more importance to its annual water status than are augmentations from the surrounding desert landscape. This is not to say that run-on is unimportant, but rather that the drainage soil is more critical in determining the effectiveness of run-on or ambient rainfall inputs to creosotebush. In major run-on events, as in the August 2000 event, the sheer volume of run-on may have overridden the differences between north and south drainage channel soils, and the surrounding surface and channel morphology characteristics of the north surface more effectively delivered this pulse to creosotebush. In contrast, the milder 2001 storms may have generated smaller amounts of run-on, but the soil characteristics of the south drainage channel were able to propagate this highly localized augmentation and that of the actual incident rainfall to the shallower rooting depths exploited by creosotebush.

4.3 Ecophysiological response of vegetation along First-order channels

The interaction of soil and climate is critical in defining pulses of plant activity that characterize desert ecology (Noy-Meir, 1973). North American warm deserts differ in the seasonal distribution of summer and winter rainfall (Smith et al., 1997). Cool-season precipitation usually comes from slow-moving, gentle rains, while warm-season storms are frequently more brief and intense. Soil developmental processes resulting in surface and sub-surface soil horizons (e.g. cemented, clay-rich) further modify climatic variation by locally controlling plant available water and subsequent plant performance. Development of strongly cemented calcic horizons, or “caliche,” is one well-known soil horizon that affects plant water relations (Cunningham and Burke, 1973), productivity (Burk and Dick-Peddie, 1974), and nutrient cycling (Lathja and Schlesinger, 1986, 1988a, 1988b; Lathja and Whitford, 1989). More recently, subtle and more widespread soil horizons have been shown to have as great an impact on desert soil hydrology and plant ecology. Silt-rich surface vesicular (Av) soil horizons, which are often associated with desert pavements of interlocking surface clasts, and clay-rich sub-surface argillic (Bt) horizons have a strong control on the depth and persistence of plant available soil water (McDonald et al., 1996; McDonald, 2002). These horizons markedly alter the effectiveness of seasonal precipitation on plant ecophysiological performance (Hamerlynck et al., 2000) and strongly impact the availability of co-limiting nitrogen resources, especially in soils with carbonate-enriched soil horizons (Lathja and Schlesinger, 1986; Lathja and Whitford, 1989).

Another important feature in desert systems is surface run-on and run-off of incident rainfall. Alterations to run-on and run-off can have pronounced effects on the seasonal water relations, productivity, and community structure of warm desert systems (Noy-Meir, 1973; Schlesinger et al., 1989; Smith et al. 1997). However, the highly unpredictable nature of run-on/run-off makes it extremely difficult to study. Many factors contribute to generating overland flow: surface roughness (Abrahams and Parsons, 1991), soil condition prior to rainfall, integrated drainage area, and the amount, duration, and intensity of the rainfall event itself (Noy-Meir, 1973; Schlesinger et al., 1989; Smith et al., 1997). And, as the case with incident precipitation inputs, there are additional factors such as channel morphology that contribute to the effectiveness of surface run-on augmentation and co-limiting nutrients to the plant community (Atchely et al., 1999).

In this portion of the project, we sought to establish a more rigorous geomorphic context in order to better understand the ecological consequences of factors affecting run-on events in desert systems. The two study sites vary markedly in age, soil horizon, and desert pavement development, resulting in first-order drainages that differ markedly in size, channel morphology, and channel soil characteristics. By coupling instantaneous water potential measurements with integrative responses such as ^{13}C isotope ratios and tissue N in three species with distinctive ecophysiological characteristics, we can use plant performance as a tool to better understand the impact of hydrological variation across a range of spatial and temporal scales.

METHODS

The evaluating relations between soils and vegetation and related ecophysiological response were evaluated through characterization of soil-hydrologic-plant linkages among six first-order drainage basins that range in size from about 10,000–48,000 m². The six drainages are located across two

extensive alluvial terraces. The upper three drainages (hereafter, north drainages) are labeled N1, N2, and N3; and the lower three drainages (hereafter, south drainages) are labeled S1, S2, and S3 (see Fig. 3.0.1).

We separated each of the six studied drainages into two plots. One plot was located along the uppermost reach of the first-order drainage (hereafter referred to as the upper channel) that has ironwood and paloverde trees. A second plot was located along the lowermost extent of the first-order channel (hereafter referred to as the lower channel) where trees lay just up-gradient from the distal end of the first-order channel. Vegetation consisting of ironwood, paloverde, and creosotebush was assessed at two plots within each of the six drainages. In two of the drainages, N1 and S3, soil properties were characterized and soil moisture was measured.

Stable Isotopes

Use of stable carbon isotopes provides insight into the supply/demand trade-offs between photosynthetic carbon uptake and evaporative water loss, or the water-use efficiency of the plant. A small portion of atmospheric CO₂ contains the heavier stable ¹³C isotope. The primary photosynthetic carbon-fixing enzyme in most plants, rubisco, discriminates against the heavier ¹³CO₂, which also diffuses slower into and out of the leaf, causing the ¹³CO₂ to accumulate in the leaf intercellular airspace. Under drying conditions, the stomata close, and there is a shift in CO₂ supply from external, atmospheric sources to internal sources, resulting in greater ¹³CO₂ uptake and incorporation into plant tissue. Thus, plant tissue ¹³C signatures provide a long-term, integrated signal of the steepness of the leaf-to-air CO₂ gradient and water-use-efficiency of the plant during growth, as determined by stomatal opening and photosynthetic capacity (Farquhar et al., 1989). Plants with high photosynthetic capacity maintain greater stomatal opening, but high physiological demand creates steep leaf-to-air CO₂ gradients, facilitating ¹³CO₂ incorporation (Farquhar et al., 1989). Photosynthetic capacity is highly correlated to relative and absolute nitrogen content in C₃ plants (Evans, 1989; Reich et al., 1995, 1998), and N-uptake is closely linked to water status (Smith et al., 1997). Thus, coupled analysis of tissue N and ¹³C data provides resolution between the contribution of stomatal supply limitations and photosynthetic capacity to integrated plant ecophysiological performance. We used the carbon isotope ratio ($\delta^{13}\text{C}$), which shows the relative abundance of ¹³C in the plant tissue against that of a standard, in this case the Jurassic limestone PeeDee Belemnite, which has a highly constant ¹³C/¹²C ratio that is distinct from any other terrestrial ¹³C source (Farquhar et al., 1989). $\delta^{13}\text{C}$ is calculated as $\delta^{13}\text{C} (\text{‰}) = [({}^{13}\text{C}/{}^{12}\text{C} \text{ sample})/({}^{13}\text{C}/{}^{12}\text{C} \text{ standard})] \times 1000$.

General Sampling Scheme Used in Water Potential and Stable Isotopes

We sampled individual ironwood, paloverde and creosotebush plants growing at the upper- and lowermost portions of three replicate first-order drainage channels on the geomorphically distinct north and south study surfaces between April 2000 and September 2001. Predawn water potential (ψ_{pd}) was measured between 00:00 and 04:00 PST using a Scholander-type pressure chamber pressurized with nitrogen gas (PMS Instruments, Corvallis, Oregon). In order to maximize sampling efficiency, all harvested samples were placed in a chilled cooler and ψ_{pd} determined less than fifteen minutes following harvest (Hamerlynck et al., 1997). Individual plants used for ψ_{pd} were marked with colored flagging and re-sampled for midday water potential (ψ_{mid}) between 11:00 to 14:00 PST.

These samples were retained, dried at 80° C for at least 48 hours, and sent to the University of Georgia Stable Isotope Facility for determination of stable carbon isotope ratio ($\delta^{13}\text{C}$) and tissue N and C content using an elemental autoanalyzer piped directly into a mass spectrophotometer.

STATISTICAL ANALYSES

We used split-plot, repeated measures, three-way analysis of variance (ANOVA) to track surface-specific performance in ψ_{pd} in each of the three species though the 2000–2001 study period. Each set of three drainages on the north and south study areas were defined as the whole-plot effect, with the surface-by-replicate drainage as the whole-plot error term. Sub-plot factors were time (day of year) and drainage location (upper and lower), using the surface-by-time-by-location-by-replicate interaction as the sub-plot error term. Of specific interest were the two-way interactions involving surface (surface-by-time or surface-by-location), and the three-way interaction (surface-by-location-by-time), since these would indicate seasonally specific differences between the surfaces in space or time. Alpha-adjusted, post-hoc general linear contrasts (t-test) were used to contrast any specific surface comparisons that might contribute to any higher-order interaction effects.

We made two distinct comparisons. The first compared the ecophysiological performance of all three species in two sampling runs following different rainfall patterns:

- Fall water availability: consisting of data from September, October and November 2000.
- Spring water availability: consisting of data from March, May and July 2001.
- Summer channel flow: consisting of data from a large convective storm in August 2000.
- Spring channel flow: consisting of data from a large frontal storm in March 2001 channel.

Prior to and during the spring run, two rainfall events occurred but did not produce marked run-on. The second comparison focused on the ecophysiological performance of paloverde stems versus ephemeral leaves produced during these two periods. Stem photosynthesis in paloverde showed greater water-use efficiency compared to that in leaves (Szarek and Woodhouse, 1978), and the two different carbon-fixation organs represented long-term (in the case of stems) and short-term (in the case of leaves) allocation aimed at optimizing water-use efficiency (Comstock and Ehleringer, 1990), and could show distinct differences in response to the soil characteristics of the north and south study sites.

Species Comparison

For the all-species comparison, a split-split-plot, repeated-measures, three-way ANOVA statistical approach was used, with surface as the whole-plot factor and surface-by-replicate drainage as the whole-plot error term. Sub-plot factors were run, using the run-by-replicate month interaction as the error term, and species, using the surface-by-run-by-month-by-replicate interaction as the error term. Drainage location was omitted from this analysis since it had been found to be of minor importance in previous results. Of specific interest were any two-way interactions involving surface, or the surface-by-run-by-species interaction, which would suggest species-specific responses to surface and time.

To compare paloverde stem and leaf photosynthetic responses, a split-plot, repeated-measures three way ANOVA statistical approach was used, with surface as whole-plot factor and the surface-by-

replicate drainage interaction as whole-plot error term. Sub-plot factors were month of sampling (two from the fall run, one from spring), tissue type, and drainage location, using the surface-by-time-by-drainage-by-replicate interaction as the sub-plot error term. Of specific interest were any two-way or three-way interactions involving tissue type, since these would indicate distinct responses by the long-term (stem) and short-term (leaf) components of carbon gain by paloverde to soil/climate variability.

In both analyses, alpha-adjusted general linear contrasts (t-test) were made for specific contrasts that might underlay any higher-order interactions. All proportional data were arcsine transformed to meet ANOVA data assumptions.

RESULTS

Water relations

Predawn water potentials (ψ_{pd}) did not vary significantly between surfaces (pooled across species and sampling period), nor did ψ_{pd} vary significantly between the fall and spring samplings (Table 4.3.1). Ironwood, paloverde and creosotebush ψ_{pd} differed significantly pooled across the two precipitation regimes (Table 4.3.1). Ironwood and paloverde averaged ψ_{pd} of -2.69 MPa and -2.76 respectively, markedly greater than levels attained by creosotebush (-5.19 MPa). However, these species differences interacted significantly with surface and sampling period (Table 4.3.2). One reason for this interaction is the invariant responses of ironwood and paloverde across surfaces and between sampling periods. Following the fall run-on event, creosotebush at the south site had significantly higher ψ_{pd} compared to south site counterparts ($t = -1.80$; $p = 0.073$), but there were no significant differences between surfaces at the springtime sampling, when rainfall did not generate run on (Fig. 4.3.1). Creosotebush ψ_{pd} showed a greater proportional increase on the south surface ($t = -4.8$; $p \leq 0.0001$) than on the north surface ($t = -2.1$; $p = 0.033$), and also had higher overall ψ_{pd} in the spring compared to the fall sampling periods ($t = -4.9$; $p \leq 0.0001$), while ψ_{pd} in ironwood and paloverde did not show any such differences (Fig. 4.3.2).

Table 4.3.1. Individual ANOVA F-test results of seasonal predawn water potential responses of desert ironwood, foothill paloverde and creosotebush growing on two differently aged geomorphic surfaces and at upper and lower first-order drainage locations from April 2000 to September 2001.

Effect	Ironwood	Paloverde	Larrea	Df
Surface (Sur)	0.06	1.53	0.86	1, 4
Location (Loc)	0.04	2.16	5.29**	1, 76
Date (D)	39.75***	46.11***	148.61***	9, 76
Sur x Loc	1.20	1.98	0.43	1, 76
Sur x D	0.79	0.92	3.87***	9, 76
Loc x D	0.44	0.88	0.46	9, 76
Sur x Loc x D	0.36	0.86	1.08	9, 76

P < 0.05; *P < 0.01

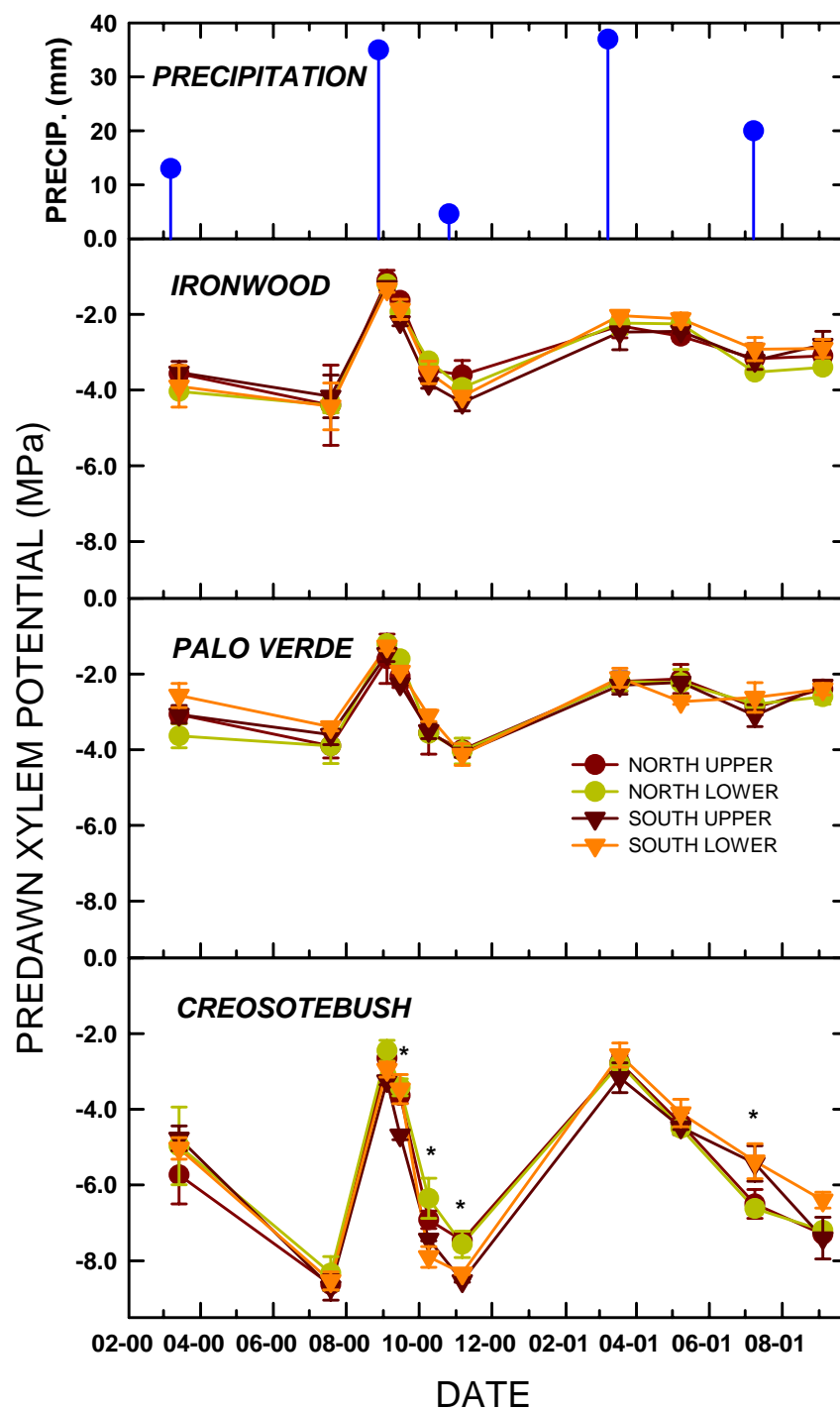


Fig. 4.3.1. 2000 and 2001 seasonal precipitation and predawn water potential of desert ironwood, foothills paloverde and creosotebush growing in upper and lower first-order drainage positions on two distinct geomorphic surfaces on the YPG, Arizona, U.S. Each point is the mean of three independent measurements, bars indicate \pm one standard error, and * indicate significant surface differences within that sampling date (t-test on ANOVA results).

Stable isotopes

Stable carbon isotope ratios ($\delta^{13}\text{C}$) differed significantly among species (-22.6 ‰, -23.4 ‰ and -23.7 ‰ for paloverde, ironwood, and creosotebush, respectively), and between sampling periods, with significant surface-by-species and sampling-by-species interaction effects (Table 4.3.2). Pooled across surface and species, $\delta^{13}\text{C}$ decreased from -22.9 ‰ in the fall to -23.6 ‰ in the spring. The

Table 4.3.2. ANOVA F-test results of predawn water potential (ψ_{pd}), tissue stable carbon isotope ratio ($\delta^{13}\text{C}$) and % N per dry weight of three Sonoran Desert woody species (desert ironwood, foothills paloverde, and creosotebush) growing in first-order drainages on two contrasting geomorphic surfaces (north and south) and two contrasting seasonal rainfall regimes (Run). Degrees of freedom are in parentheses; results for N are from arcsine-transformed data. Significant effects are highlighted in bold.

Effect (df)	ψ_{pd} (MPa)	$\delta^{13}\text{C}$ (‰)	N (% DW)
Surface (1, 10)	0.56	0.01	5.37**
Run (1, 8)	0.36	34.39***	10.02**
Species (2, 50)	716.34***	18.83***	280.24***
Sur x Run (1, 8)	0.11	2.64	0.82
Sur x Spp (2, 50)	1.40	3.63**	1.53
Run x Spp (2, 50)	41.29***	10.46**	8.35***
Sur x Run x Spp (2, 50)	9.44***	1.29	0.02

P < 0.05; *P < 0.01

surface-by-species interaction is due to consistently lower $\delta^{13}\text{C}$ in ironwood on the north surface compared to south site plants ($t = -2.86$; $p = 0.005$), and the lack of significant variation in creosotebush and paloverde between the surfaces (Fig. 4.3.4). Similar dynamics underlie the sampling-by-species interaction, where paloverde showed no significant change in $\delta^{13}\text{C}$ from fall to spring, while both ironwood ($t = 3.06$; $p = 0.0025$) and creosotebush ($t = 7.54$; $p \leq 0.0001$) $\delta^{13}\text{C}$ declined significantly (Fig. 4.3.2).

Nitrogen

Plants on the north surface had significantly higher N content (2.22%) compared to south surface plants (2.10%; Table 4.3.2). N content also declined significantly from fall (2.31%) to spring (2.01%) sampling periods, and it varied significantly between species (Table 4.3.1). Ironwood had the highest average N (2.81%), with intermediate levels in creosotebush (2.14%) and lowest N in paloverde stems (1.54%). There was a sampling-by-species interaction (Table 4.3.2). Ironwood and paloverde showed marked declines in N going from Fall to Spring ($t = 7.24$ and 2.88 ; $p < 0.0001$ and 0.0173 , respectively), while creosotebush showed more moderate, but still significant, declines in tissue N between fall and spring ($t = 2.17$; $p = 0.032$; Fig. 4.3.4).

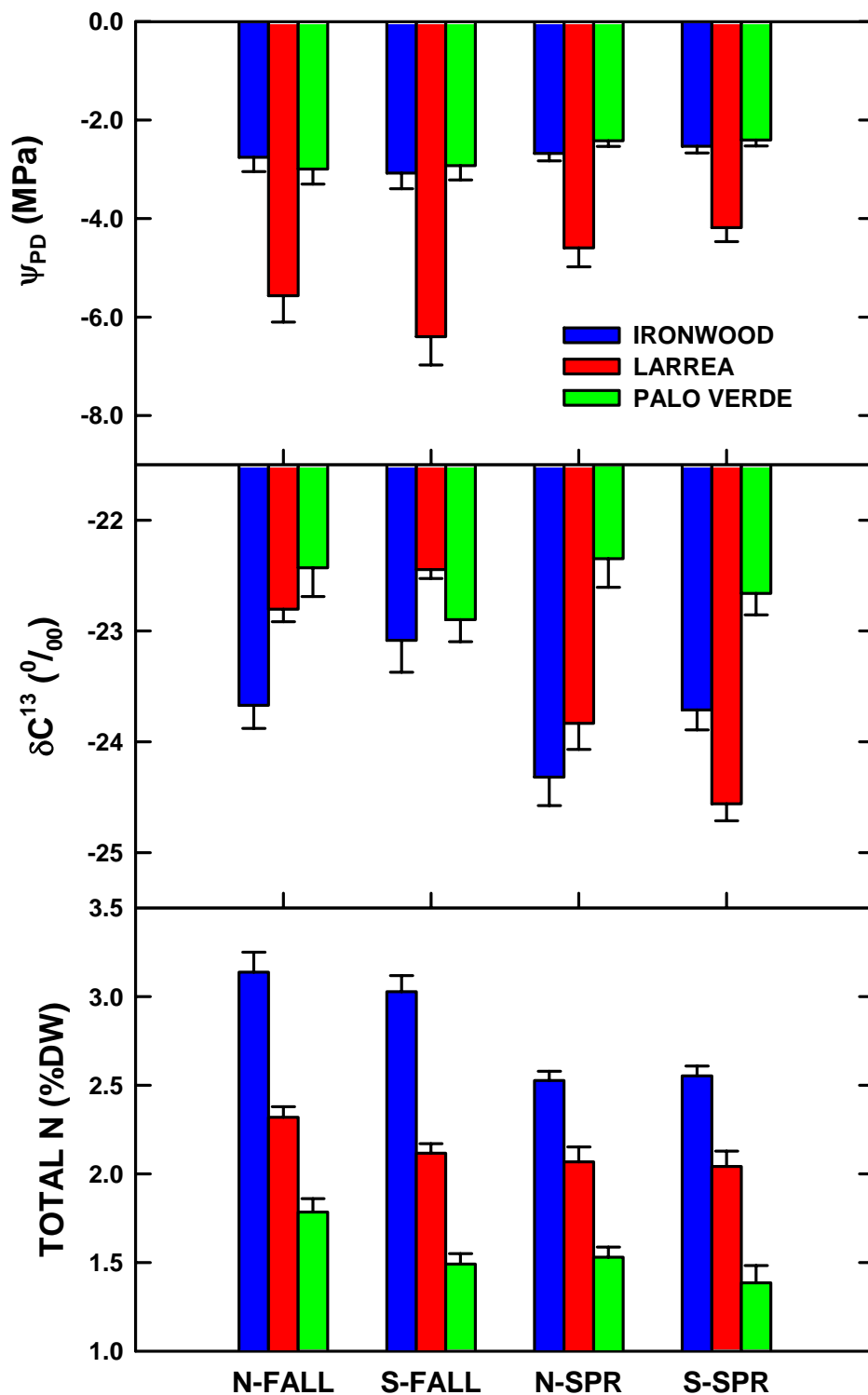


Fig. 4.3.2. Predawn water potential (Ψ_{pd}), stable carbon isotope ratios ($\delta^{13}C$) and tissue N (% dry weight) for desert ironwood, foothills paloverde and creosotebush growing in first-order drainages on two distinct geomorphic surfaces on the YPG, Arizona, U.S. under rainfall regimes that produced (fall) or did not produce (spring) significant amounts of run-on. Each bar is the mean of six measurements, error bars are \pm one SE.

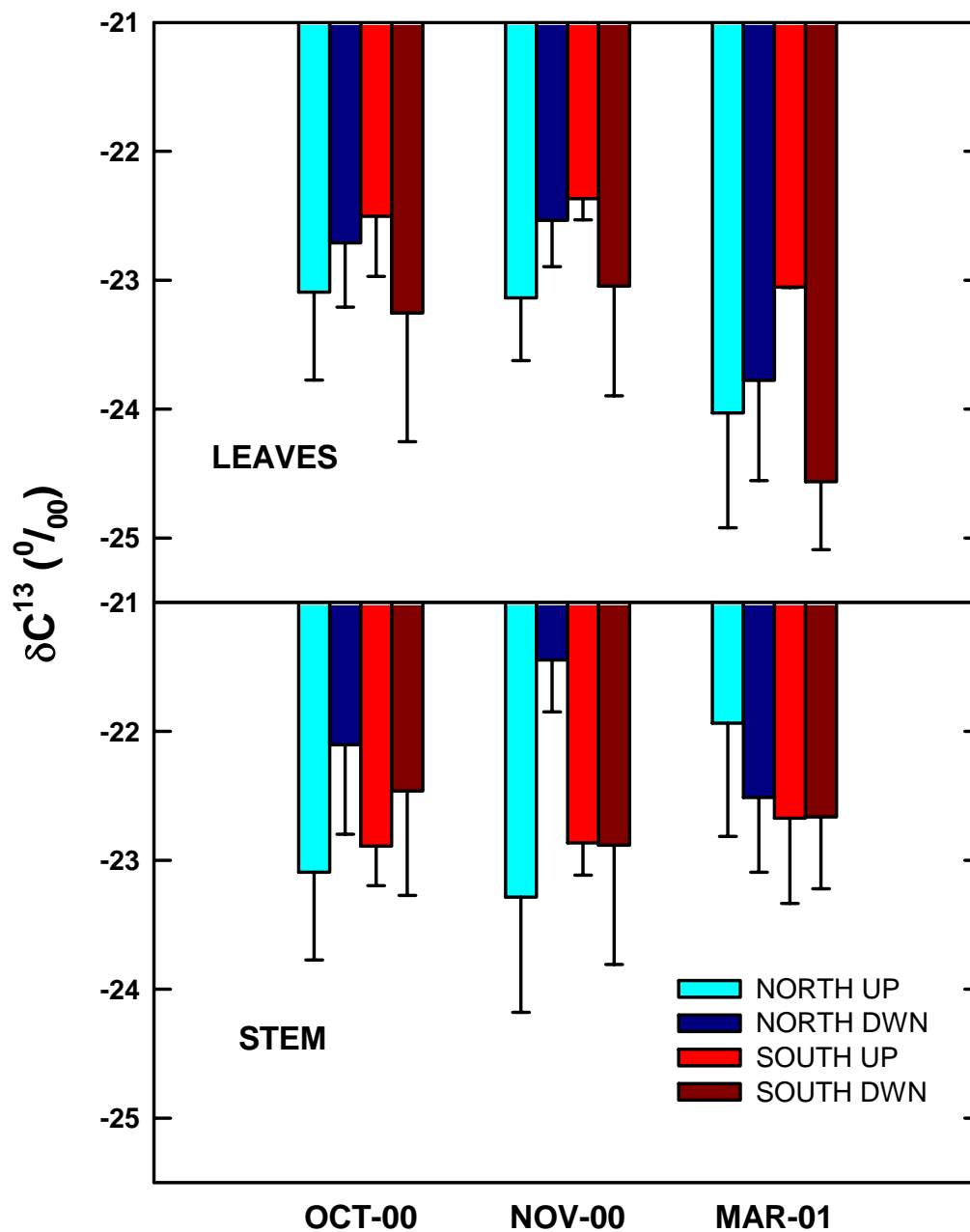


Fig. 4.3.3. Leaf and stem stable isotope ratios ($\delta^{13}\text{C}$) of foothills paloverde growing at upper and lower drainage locations on two distinct geomorphic surfaces on the YPG, Arizona, U.S. October and November measurements were made following a significant run-on event; March measurements are not. Each bar is the mean of three independent measurements, error bars are \pm one SE.

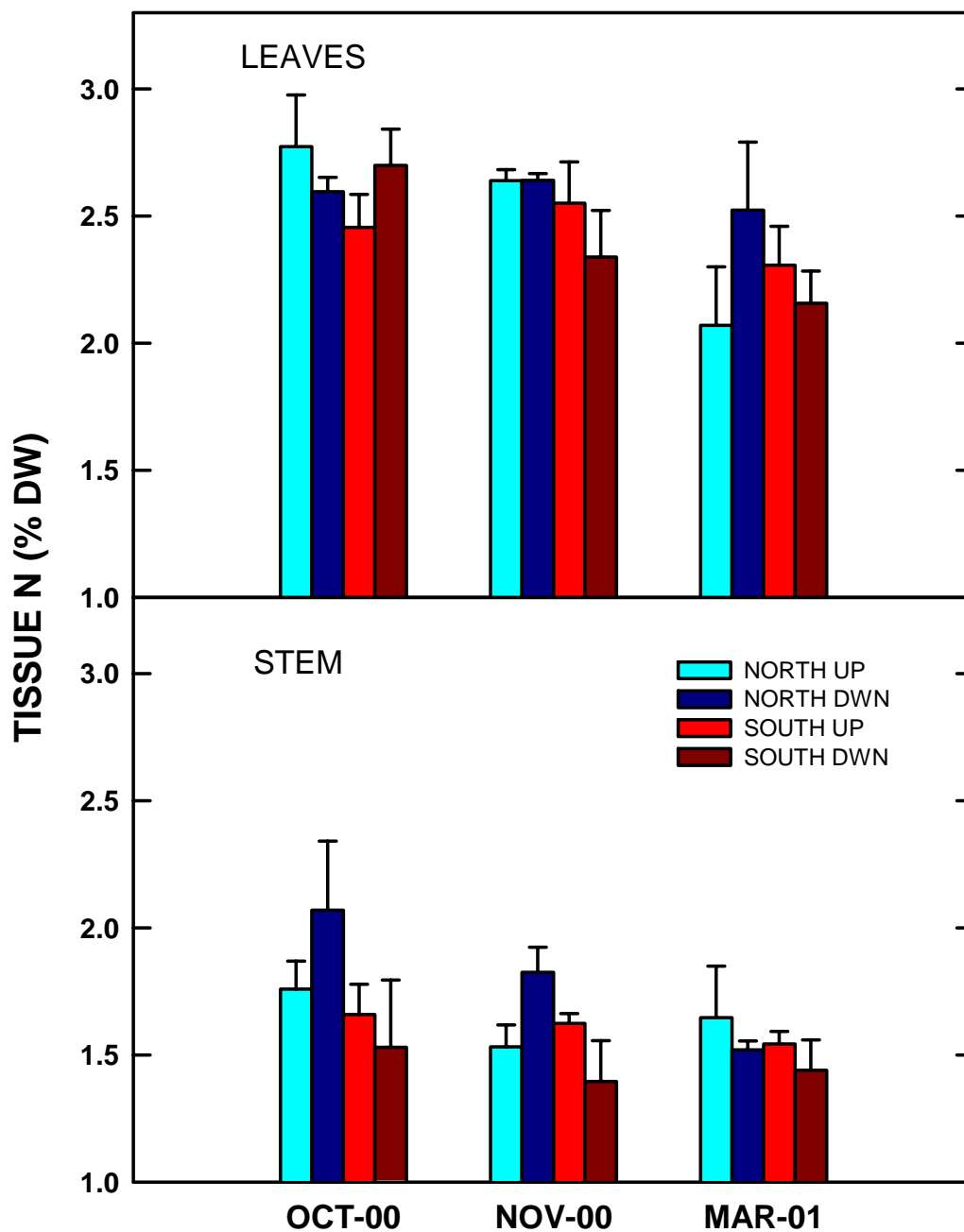


Fig. 4.3.4. Leaf and stem nitrogen (% dry weight) of foothills paloverde growing at upper- and lower-drainage locations on two distinct geomorphic surfaces on the YPG, Arizona, U.S. October and November measurements were made following a significant run-on event; March measurements were not. Each bar is the mean of three independent measurements, error bars are \pm one SE.

Paloverde Stem and Leaf Comparisons

Paloverde stems and leaves significantly differed pooled across sampling periods and study sites. Mean stem $\delta^{13}\text{C}$ was -22.5 compared to -23.1 in leaf tissue, while N content in stems (1.63%) was significantly lower compared to leaves (2.48%; Table 4.3.3). Two of the sampling periods (October and November) were made after the large August run-on event, while the spring 2001-precipitation regime resulted in leaf production produced only in one month (March, 2001). Stable C-isotope responses showed significant surface-by-location, location-by-time, and location-by-tissue and tissue-by-time interactions (Table 4.3.3). The first interaction was due to differences between north and south surfaces at lower-drainage locations ($t = 1.70$; $p = 0.095$), while upper-drainage locations did not differ (Fig 4.3.3). This interaction was likely driven by larger changes in $\delta^{13}\text{C}$ in stems compared to leaves during the October and November sampling periods (Fig. 4.3.3). The location-by-time interaction was due to lower $\delta^{13}\text{C}$ in March compared to levels pooled across October and November ($t = -2.10$; $p = 0.041$), likely due to greater declines in leaves. Tissue differences were also location-specific, with leaf and stems differing in $\delta^{13}\text{C}$ at lower drainage locations ($t = -2.62$; $p = 0.012$), with no location differences within leaf or stem $\delta^{13}\text{C}$. The tissue-by-time interaction was due to within- and between-tissue responses through time. Stem $\delta^{13}\text{C}$ did not change significantly between samplings, while leaf $\delta^{13}\text{C}$ ratios in March were lower than in October ($t = -2.13$; $p = 0.038$) and November ($t = -2.39$; $p = 0.021$), while $\delta^{13}\text{C}$ did not differ between the two fall sampling dates. In addition, only in March did wood and leaf $\delta^{13}\text{C}$ differ significantly from each other ($t = -3.11$; $p = 0.003$).

Table 4.3.4. ANOVA F-test results of seasonal tissue stable carbon isotope ($\delta^{13}\text{C}$) and nitrogen content of photosynthetic stems and leaves of foothills paloverde growing at upper and lower drainage locations in first-order drainages on two distinct geomorphic surfaces. Significant main and interaction effects are highlighted in bold text.

Effect	$\delta^{13}\text{C}$ (‰)	N (%DW)	df
Surface (Sur)	0.10	11.39**	1, 4
Location (Loc)	0.03	0.05	1, 43
Time (Mo)	2.92*	7.07**	2, 43
Tissue (Tis)	15.75***	179.01***	1, 43
Sur x Loc	6.27**	3.04*	1, 43
Sur x Mo	0.05	0.41	2, 43
Sur x Tis	2.16	0.31	1, 43
Loc x Mo	3.67**	0.20	2, 43
Loc x Tis	4.87**	0.03	1, 43
Mo x Tis	4.61**	1.05	2, 43
Sur x Loc x Mo	1.57	0.73	2, 43
Sur x Loc x Tis	1.86	0.51	1, 43
Sur x Mo x Tis	0.11	0.32	2, 43
Loc x Mo x Tis	0.18	0.94	2, 43
Sur x Loc x Mo x Tis	1.52	2.91*	2, 43

* $P < 0.1$; ** $P < 0.05$; *** $P < 0.01$

Leaf and stem nitrogen contents also showed considerable temporal and spatial variability (Fig. 4.3.6). In addition to significant tissue differences, north surface plants had higher pooled N content (2.13%) compared to south surface counterparts (1.97%; Table 4.3.4), and pooled stem and leaf N was significantly lower in March (1.90%) compared to October and November (2.2 and 2.1%, respectively). There were two mildly significant interactions: surface-by-location and surface-by-location-by-tissue-by-time (Table 4.3.4). The former was due to higher N in north (2.20 %) compared to south plants (1.93%) at lower drainage locations, while no surface differences occurred in upper-drainage plants. The four-way interaction suggests that wood and leaf N-dynamics are very different across the landscape and through time (Fig. 4.3.6). Likely, the contrast driving this interaction is that leaf N does not show consistent variation across the surfaces and drainage locations, while stronger differences are apparent in wood-N content (Fig. 4.3.6). For example, in the fall, wood N is significantly higher in paloverde from the lower north surface drainage locations compared to all other locations ($t = -2.92$; $p = 0.0054$), while in leaves, there is no such corresponding pattern. In contrast in March, leaves from northern lower-drainage plants have greater N compared to leaves from all other sites ($t = -1.96$; $p = 0.056$), while no distinguishable differences in wood N are apparent (Fig. 4.3.6).

DISCUSSION

The three-species comparison clearly shows that ironwood and paloverde primarily rely on deeper and more temporally constant soil water. This is best seen by the invariant ψ_{pd} response of these two species compared to the marked changes in ψ_{pd} in creosotebush (Fig. 4.3.4). Ironwood and paloverde use this deep soil water source quite differently, which can be attributed to the different stomatal behavior in leaves (in the case of ironwood) and photosynthetic stem tissue (in the case of paloverde). Stable carbon isotope ratios ($\delta^{13}C$) were quite different between ironwood and paloverde, with ironwood showing considerable lower and more variable $\delta^{13}C$ compared to paloverde. Stem photosynthesis is under much greater diffusive limitation compared to leaves, due to low stomatal opening and low stomatal density (Comstock and Ehleringer 1990). This results in very high plant water-use efficiency in paloverde compared to ironwood and creosotebush (Fig. 4.3.4).

Even though ψ_{pd} suggests that soil water availability was similar between surfaces for ironwood, $\delta^{13}C$ was consistently more negative on north surface plants, and showed a marked decline from fall to spring (Fig. 4.3.4). The lower $\delta^{13}C$ on the north surface suggests that this soil/drainage system permits ironwood to keep its stomata open over longer periods than south surface plants. This is in agreement with our hydrological and growth data that suggest that run-on is more effective in augmenting soil moisture to depth in north surface first-order drainages (Hydro figure and basal diameter+diameter/distance figure). Thus, it may be that ironwood adjusts stomatal opening in order to regulate transpirational water loss and maintain soil water reserves at an acceptable level. This is very similar to how obligate phreatophytes respond to alterations in soil water table dynamics (Smith et al., 1997).

The marked decline in $\delta^{13}C$ going from fall to spring is in part due to seasonal patterns in photosynthetic capacity, as evidenced by tissue N (Fig. 4.3.4). In the fall, leaf N was significantly greater, suggesting higher photosynthetic capacity (Evans 1989; Reich et al. 1998). Plants with high photosynthetic capacity keep high demand well supplied by increasing stomatal opening. High

photosynthetic rates rapidly reduce internal CO₂ concentrations, thereby increasing ¹³C uptake and lowering δ¹³C values (Farquhar et al., 1989). Another contributing factor might be that the earlier run-on was sufficiently augmented by shallower incident rainfall inputs during the spring rains, and ironwood increased stomatal opening to capitalize on this more transient water resource. This behavior has been noted in phraeatophytic species with extensive lateral root systems (Smith et al., 1997), and might also be expressed in this more variable soil water environment.

The ψ_{pd} , δ¹³C and N data for creosotebush are consistent with responses primarily determined by shallower soil water (Hamerlynck et al., 2000). Thus, δ¹³C in creosotebush is consistent with changes in ψ_{pd} , which were significantly lower following the fall run-on event compared to the spring rainfall regime (Fig. 4.3.2). This suggests that during the fall, the infiltration of water to depths below the creosotebush rooting zone and lack of additional rain sufficient to wet soils to any depth (Fig. 4.3.2) resulted in greater stomatal restriction of transpirational water loss. The two fairly large, less intense spring storms effectively recharged the upper soil profile, improving water status and increasing stomatal opening, thereby lowering δ¹³C (Fig. 4.3.2).

Paloverde showed markedly lower variation in its growth (basal diameter figure) and ecophysiological responses compared to ironwood and creosotebush (Fig. 4.3.2). This would suggest that the strong stomatal limitations associated with stem photosynthesis reflect lower amplitude of stomatal response to environmental variability (Szarek and Woodhouse, 1978; Comstock and Ehleringer, 1990). Comparison of leaf and stem performance yielded few readily interpretable results. The clearest contrasts were the pronounced seasonal differences in δ¹³C in leaves, which have greater stomatal opening as reflected by lower δ¹³C (Fig. 4.3.3), and likely respond to more fluctuating variables such as declining soil moisture, humidity, temperature and light (Szarek and Woodhouse, 1978; Comstock and Ehleringer, 1990). This pattern also supports assertions that deep and shallow water sources are partitioned between stem and leaf gas exchange (Szarek and Woodhouse, 1978; Smith et al., 1997), but this would require use of oxygen or hydrogen isotope analysis to ascertain more accurately (Donovan and Ehleringer, 1994). However any integrative soil-specific effects, such as the significant surface-by-location interaction (Table 4.3.3) were driven by marked increases in stem δ¹³C in north surface plants in the fall, and a decreases in leaf δ¹³C in south surface plants at lower drainage locations in March (Fig. 4.3.3). This does not allow clear resolution of the interaction of these two functional features within the entire soil context. This was not the case for ironwood and creosotebush, which, when analyzed separately, did not show any significant contribution of drainage position to this interaction (data not shown). It is interesting to note that high stem δ¹³C was concurrent with high N-content (Fig. 4.3.4), suggesting that photosynthetic demand could contribute to this pattern, as was the case in ironwood (Fig. 4.3.3), and in paloverde leaves, where highest δ¹³C and N occurred in the fall (Figs 4.3.3 and 4.3.4). These findings further support evidence that large-run events deliver greater soil water and nutrient pulses, and that the hydro-geomorphology of the north surface delivered run-on more effectively to deeper soil depths.

5.0 Conclusions

The overall goal of this project was to determine if selected shrub and tree species distributed along first-order channels draining desert piedmonts can provide efficient and reliable signals of environmental change (resulting from either natural disturbance or military activities) as well as ecological condition. Results demonstrate that a direct link exists between surface runoff and ephemeral channel flow and ecological condition. This indicates that knowledge of how changes in environmental factors that control surface runoff, especially land use and climatic variation, can be integrated with assessment of biological activity to develop effective strategies to monitor ecosystem condition in arid and hyper-arid areas. Specific project conclusions, supporting results, and management recommendations according to project objectives are summarized in Tables 1-3. Important implications of results and conclusions are discussed below.

HISTORIC RANGE IN DESERT VEGETATION ALONG FIRST-ORDER CHANNELS

Disruption of ephemeral surface flow along first-order (and higher order channels) will result in a decrease in trees and shrub density and overall biodiversity and will likely result in an increase in abundance of non-native species. A change in vegetation results from either blocking or limiting flow along channels or by destroying soil surfaces that are conducive to producing surface runoff into adjacent channels. Analysis of the distribution of live and dead ironwood and paloverde provide no clear record of historic change in ecologic condition, but relations between tree trunk diameter and size of drainage basin suggest that larger trees may be the most susceptible to decreases in surface runoff and channel flow.

Analysis of the origin and distribution of features we define as plant scars (circular features of bioturbated soil 2-5 m in diameter) indicate that long-term changes in ecosystem condition are also occurring. Plant scars form conspicuous and highly visible features that are nearly ubiquitous across the desert piedmonts common to YPG and hyper-arid to arid reaches of the desert Southwest. Results indicate that the creation of plant scars is due to a contraction of vegetation from soil surfaces and into the marginal drainage channels. The onset of changes in ecological condition appears to predate military land use and probably reflects long-term changes in climate that began decades to centuries before establishment of YPG. Long-term changes in soil development may be also partially responsible for the development of the plant scars.

5.1 RELATION BETWEEN SOIL AND SURFACE HYDROLOGY AND ECOSYSTEM CONDITION

Role of soil/pavements in providing runoff

Soil characterization results demonstrate the strong contrast in properties between the soils common to the first-order channels and soils underlying the surrounding desert pavement. Across most of YPG (as well as most arid areas in the desert Southwest), soils surfaces that readily produce surface runoff are associated with desert pavements. Infiltration rates into desert pavements are considerable low and are likely to produce surface runoff during either high intensity storms or storms of long-duration. The primary reason for low infiltration rate in areas marginal to first-order channels is the accumulation in near-surface soil horizons of aerosolic dust that is rich in silt- and clay-sized

particles. By contrast, infiltration is relatively higher in soils along ephemeral channels and is conducive to transmission loss.

Results indicate that precipitation rarely exceeds the amount required to infiltrates below surface horizons and into the underlying soil in both channels and soils marginal to channels. This indicates that augmentation of plant available moisture, especially along channels, from surface runoff and channel flow is required. Depth profiles of soluble salt content for soils across first-order drainage basins demonstrate that the depth of transmission loss along first-order channels occurs frequently enough to prevent the pedologic accumulation of soluble salts in channel soils.

Although channel flow and transmission loss occurs episodically, the frequency is low with respect to supplying water to vegetation along first-order channels. An additional important finding of this study is the limited occurrence of surface run-off of sufficient magnitude to create channel-flow. Field observations indicate that although storms may occasionally produce limited, localized runoff, storms that have the precipitation of adequate intensity or duration to produce adequate channel flow are infrequent and may only occur once every three to six years. Channel flow and volume, therefore, is highly episodic and only occasionally of high volume.

Relation of Plant Dynamics to Drainage Hydrology

Project results indicate that environmental factors that control surface flow of water are the primary elements controlling ecosystem condition, especially the dynamics of ironwood and paloverde. First, there is a considerable decrease in vegetation species abundance and type downstream of areas that lose surface flow. Second, ecophysiological responses (plant tissue isotopic analysis and water potential) clearly show that ironwood and paloverde primarily rely on deeper soil water (> 2 m depth) that is a more consistent source of plant-available moisture relative to near-surface soil water. The source of this water is not ground water, but is likely to be zones or layers of sediment that contain plant –available soil moisture. By comparison, creosotebush may use deeper water, but appears to be more responsive to changes in soil water in the near-surface soil (< 1m depth). The source of the deep soil moisture in first-order channel soils is from transmission loss (percolation of water into the soil) during rare, episodic surface flow events.

Importance of Infrequent Large Storms

Project results suggest that although storms may occasionally produce limited, localized runoff, storms that have the precipitation of adequate intensity or duration to produce channel flow that provide substantial transmission loss and deep percolation into channel soils are infrequent. These very large storms likely generate considerable flow that substantial fills the channel and is likely maintained for hours – may be the most important ecological drivers in this desert ecosystem. These types of channel flow events may be primarily associated with typical cyclones or depressions that episodically move northward and into the southwest U.S. Tropical storms or depressions may only occur once a decade, but may provide a substantial source of deep recharge of plant-available water for vegetation along first-order and higher channels.

5.2 IMPLICATIONS OF PROJECT RESULTS

Role of Military Activities on Ecologic Condition

Combining information about precipitation, channel flow events, and measured plant response demonstrate that long-term survival of ironwood and paloverde require semi-annual surface runoff and channel flow. Military land use activities, therefore, that change the frequency of amount of surface flow along low-order channels will directly impact ecological condition of vegetation along channels. Severe disruption to desert pavements and the underlying fine-texture vesicular A (Av) horizon will likely result in considerably higher infiltration and in profound decrease in surface runoff, and in turn, a decrease episodic channel flow will ultimately and severely impact desert vegetation. Construction of dikes, barriers, or road across low order drainage channels will also impact biodiversity along channels.

Use of first-order drainages form monitoring ecosystem condition: Best indicator of change?

Project results indicate that monitoring vegetation along first-order channels may provide important information about overall ecologic condition. Clearly decreases in biodiversity of vegetation abundance along first-order channels will indicate that a change in surface flow has occurred. The overall project hypotheses suggested that changes in vegetation along a first-order drainage would provide the best indicator of ecologic condition because first-order drainages are the top of the water distribution network. Any change in ecologic condition, therefore, would first appear along first-order channels because vegetation along higher order channels is more likely to receive surface flow during any large precipitation event and an overall greater contributing drainage area. Our findings, however, suggest that overall first-order drainages may be less sensitive to perturbation than we thought. Vegetation along first-order channels is inherently the most prone to drought because localized run-on and run-off play a greater role in immediate input of water to the plant community. The size of ironwood and paloverde are generally smaller relative to the size of these trees along higher order channels. Results from this study indicate that the basal diameter of trees will generally increase with increasing channel distance (and a greater contributing source area for runoff). Other studies have established that there is a generally a tight relationship between growth and leaf area, which is usually scalar, in desert plants. Trees with bigger trunks are required to maintain a bigger transpirational leaf area, since leaf-area to sapwood areas are usually consistent. Larger trees along higher order channels, therefore, may prove to be more sensitive to changes in surface flow and deep recharge of channel soil. In other words, larger trees along higher order channels are conditioned to receive channel flow more often or have a greater reserve of deep soil moisture (i.e. larger channels have greater corresponding transmission loss). In either case, a decrease in the supply of surface flow may impact larger trees first. If this relation is true, an increase in tree mortality along higher order channels may provide an earlier indicator for change in ecological condition.

Ironwood: The best Indicator of Ecologic Change

Project results indicate that the most reliable species for monitoring ecologic condition is ironwood. The combination of durable wood with deep rooting habit and reliance on evergreen leaves make this species an excellent integrator of the important hydrological, and therefore ecological, driving

variables in this severely water-limited system. Moreover, as mentioned above, there is a strong relationship between growth and leaf area. This is likely why ironwood is so susceptible to mortality—if something interrupts effective transmission to deep soil, maintaining the water cost is too great to match respiratory load, and the plant starts to die off. Overall, water use in paloverde is much more constrained, since most of the physiological activity is through the stem, which has much higher WUE. Ironwood also displays strong relations between tree size and distance and distance to drainage head. By comparison, Paloverde and Larrea appear to be more transient species, with higher population turnover rates, and therefore do not reflect these differences as clearly. Selective monitoring of the condition of ironwood may provide one the best tools for monitoring ecologic condition of vegetation along drainage channels in arid and hype-arid regions where it grows.

6.0 Transition Plan

The results of this project demonstrate that incorporation of some of the techniques and strategies for soil and hydrologic characterization used in this project will be beneficial to conservation managers, especially when integrated with assessments of desert ecology. Incorporation of soil and hydrologic characterization with other projects at DoD installations, especially the Army's Integrated Training Area Management (ITAM) program, is actively occurring through ongoing Desert Research Institute projects involving desert soil and hydrologic characterization and restoration ecology. We have participated with Dr. Kent Ostler and Dr. Dennis Hansen on SERDP project No. CS-1131. Project results have been incorporated into current projects at the National Training Center (NTC), Ft. Irwin, California (Army), Edwards Air Force Base, and the Nevada Test Site (DOE). We have attempted to inform a wide variety of land managers through attendance at conferences and workshops, oral and poster session presentations, site visits to federal agencies, and collaboration with other researchers.

STRATEGY FOR IMPLEMENTATION OF PROJECT RESULTS BY LAND MANAGERS

Many DoD installations and other federal land holders traditionally have conservation staff with expertise in desert vegetation; however, often lack staff with expertise in desert soils, geomorphology, and hydrology. Implementation of methods and techniques used in this project will likely require contracting with geotechnical experts who specialize in research and analysis of desert soils, surface water and soil hydrology. Geotechnical experts can coordinate activities with land managers and local biologic experts to maximize resources and enhance development of cost-effective strategies for monitoring and assessing ecologic condition. We suggest land managers consider incorporating the following technical strategies for increasing the overall effectiveness of efforts for monitoring ecologic conditions:

Soil Characterization: Evaluation of soil morphology, landscape position, and key physical and chemical properties should be expanded. Although some of this information is available in soil surveys, the quality of this information is often limited because of (1) most installation surveys are of low resolution and commonly combine multiple soil types into single soil mapping units (soil associations), landscape position and relation to surface and subsurface water movement are not considered. Attention should be focused on how soil properties may

control plant distribution and the supply of plant available moisture. Most ecologic surveys and analysis rarely incorporate adequate knowledge of the relation between vegetation dynamics and soil-landscape relations. Key characteristics should include surface cover type and lateral extent, soil morphology, landscape position, vertical distribution of soil texture, calcium carbonate and more soluble salts, and depth to root restrictive layers.

Hydrologic Characterization: Desert soils will have a profound impact of the supply of plant available moisture. Knowledge of how soils control infiltration, storage, and runoff, need to be incorporated into monitoring desert ecosystems. Techniques should include measures of soil infiltration and capacity for generating runoff and monitoring of soil moisture over primary growing seasons. Integration of soil water balance with measurements of plant water potential will add determination of soil-plant linkages.

PRESENTATIONS OF PROJECT RESULTS

The methods, results, and conclusions from this project have been presented in a wide variety of venues and across a broad spectrum of audiences, including forums frequented by land managers. Presentations included both oral and posters. All presentations generated positive comments and much interest regarding our approach, results, and recommendations.

List of Presentations with Published Abstracts

- Caldwell, T.G., McDonald, E.V., Young, M.H., 2003, Modeling soil moisture in support of revegetation of military lands in arid regions, AGU Fall Meeting, San Francisco.
- McDonald, E.V., and Mouat, D., 2003, A strategy for using soil surface information to assess risk to desertification and global security, NATOCMS and Science Committee Workshop on Desertification in the Mediterranean Region: A Security Issue: Valencia (Spain), 2-5 December 2003
- McDonald, E.V., 2003, Record of late Quaternary climate change in calcic soils: interpretation of soil geomorphology and hydrologic modeling, XVI INQUA (International Union of Quaternary Scientist) Congress programs with abstracts, p. 194.
- Dahan, O., McDonald, E.V., Young, M., 2002, Water content measurements in the deep vadose zone using a new design and installation technique of TDR probes, AGU Fall meeting, San Francisco.
- McDonald, E.V., and Morrill, V., 2001, Developing effective ecosystem monitoring strategies for military activities in deserts: results from the Yuma Proving Ground. 10th Annual US Army Integrated Training Area management Workshop and Proceedings, Nashville, TN, August 27-30.
- McDonald, E.V., Bruier, F., J., McAuliffe, and Morrill, 2001, Evaluating the significance of cleared circles on military lands in the desert southwest U.S.: Formation due to active rodents or weary humans? 10th Annual US Army Integrated Training Area Management Workshop and Proceedings, Nashville, TN, August 27-30.
- McDonald, Eric, Bruier, Frederick, and Joseph McAuliffe, 2000, Interaction of soil and biologic processes in the formation of cleared circles in the desert southwest: Active rodents or weary humans? Geological Society of America Annual Meeting, Reno, NV, November 12-16.

- McDonald, Eric, Erik Hamerlynck, Joseph McAuliffe, and Valerie Morrill, 2000, Developing effective ecosystem monitoring strategies for military activities in deserts: preliminary results from the US Army Yuma Proving Ground, 9th Annual ITAM Workshop, p. 59.
- Sparks, Ruth and McDonald, Eric, 2000, A landscape dynamics modeling approach to integration of LCTA and LRAM components. 9th Annual ITAM Workshop, p. 41.
- McDonald, Eric, Bruier, Frederick, and Joseph McAuliffe, 2000, Determining the cultural significance of cleared circles at the Yuma Proving Ground, SERDP Technical Symposium and Workshop, Nov. 28-30.
- McDonald, Eric, Erik Hamerlynck, Joseph McAuliffe, and Valerie Morrill, 2000, Developing effective ecosystem monitoring strategies for military activities in deserts: preliminary results from the US Army Yuma Proving Ground, SERDP Technical Symposium and Workshop, Nov. 28-30.

INVITED LECTURES

Pedologic Processes, Landscape Dynamics, and Ecological Patterns on Desert Piedmonts, Southwest. Washington State University Department of Crops and Soils (April, 2000).

PUBLICATIONS:

- Dahan, O., E.V. McDonald, and M.H. Young. 2003. Development of a flexible TDR probe for deep vadose zone monitoring, submitted to Soil Science of America, *Vadose Zone Journal* 2:270-275.
- McAuliffe, J.R., and E.V. McDonald. 2003. Persistent plant scars on desert pavements: long-term records of environmental change in the Sonoran Desert: Submitted to *Nature* (in review)

YPG COMMUNITY OUTREACH:

Two posters, presented at the SERDP Workshop in 2000, were submitted to YPG. These posters have been on display at YPG and are frequently used in support of community outreach by the YPG personnel. A new version of this poster—designed for the general public—is under development and will be presented to YPG this spring.

7.0 Recommendations for Future Work

Our findings suggest that cost-effective and scientifically sound strategies for monitoring ecologic condition should incorporate methods and techniques for soil and hydrologic characterization. Moreover, results also confirm that monitoring key vegetation along first-order, as well as higher order channels, will provide an effective way to monitor ecosystem condition. We also suggest that further refinement of ironwood as a monitoring species is required. Based on our understanding gained in this study, and additional field observations, we suggest developing three possible sampling strategies:

- 1) **Monitoring of whole-plant water use across a range of drainage types.** Our findings suggest that first-order drainages may be less sensitive to perturbation than we thought.

As the most drought prone portion of the drainage, localized run-on and run-off play a greater role in immediate input to the plant community. Monitoring whole-plant water use using heat-pulse dissipation sap-flow meters might provide a better quantification of the actual water use by the plant, and help establish critical water requirement for sustaining growth and reproduction across the range of drainage basin sizes potentially impacted by training or mission-related activity. Sap-flow techniques have been shown useful in establishing soil-effects on desert plant water use (Smith et al. 1995) and in response to hydrological perturbation (Smith et al. 1991), and is the best approach available to determine whole plant water use with non-destructive methods.

- 2) **Leaf Pubescence.** We have observed a visually distinct change in the amount of leaf pubescence between ironwood plants growing in larger and smaller washes. Leaf pubescence alters the spectral signature of the entire canopy, and is a critical feature in the energy balance and water-use strategy in woody desert plants (Ehleringer 1982). Field spectroradiometer monitoring, either via airborne or ground-based sampling schemes, could be used to track changes in leaf pubescence across surfaces, within drainages, or between hydrologically impacted plant communities. This technique is all the more attractive in that it can be scaled up, and leaf pubescence dynamics can be put into a “spectral landscape” context that would relate fundamental aspects of plant performance to landscape hydrology.
- 3) **Incorporation of different stable isotope analyses.** Comparing the stable hydrogen and oxygen isotope contents of plant tissue to that of incident rainfall can provide critical insight on determining the sources and seasonal impacts of soil water used by plants (Smith et al. 1997). If such measurements were made concurrent with stable carbon isotope, spectral and sap-flow measurements, ironwood could provide integrated insights on temporal dynamics ranging from days to years, and across spatial scales from tens to thousands of square meters.
- 4) **Experimental flexible TDR probes.** We have developed and tested a new and innovative type of soil moisture probe that can be used to monitor soil moisture at depths between 2 and 10 m (Dahan, et al., 2003). Two key aspects of this probe is that it allows emplacement of the probe into undisturbed soil (currently a problem with soil deep probes) and soil moisture can be monitored continuously. A version of this probe is currently being beta-tested at YPG and in Israel. Additional testing and development of this probe in conjunction with plant-water use studies will allow assessment of how trees utilize soil moisture at depths > 2m, how frequently this plant-available moisture is replenished, and rate of transpirational extraction. This type of probe technology can also be used to monitor pro-active augmentation of water (as part of a remediation plan) and to monitor impacts of land use activity on surface flow and transmission loss along channels. No other currently available technology can provide this type of soil moisture information.
- 5) **Establish surface runoff and channel flow monitoring for areas of extensive disturbed desert pavements.** Further analysis of relation between precipitation among, frequency, and duration is warranted. Results from this project suggest that surface runoff is frequently generated, but that the flow is not sustained for enough time to generate

channel flow. Establishment of additional sites for monitoring channel flow and surface runoff will help land managers better understand how impacts to soil surface and /or changes in precipitation patterns will effect surface runoff.

- 6) **Continuation of soil moisture monitoring.** Results from this project demonstrate that knowledge of temporal changes in soil moisture is essential for determining both the source and status of plant available water. A wide assortment of soil probes (moisture, volumetric potential, temperature, flux meters) are commercially available; however, developing the correct strategy for monitoring (i.e. which type of probe to use) still requires expert advice. Moreover, the installation and data interpretation for all of these probes in coarse-texture desert soils still requires further analysis to better quantify data quality. We recommend that land managers increase monitoring of soil moisture, especially when combined with soil landscape and hydrologic characterization.
- 7) **Numerical modeling.** Numerical models of soil-water balance provide a means to directly link the physical and hydrologic characteristics of the soil, site meteorological conditions, and ecologic condition. Several soil hydrologic models are available but most of these have been developed and tested for agricultural settings and have not been extensively modified and tested for gravel-rich desert soils. Moreover, state-of-the-art simulation codes still require some improvement to address different boundary conditions (e.g., soil evaporation, climate) from remote-sensing platforms. Additional effort to advance numerical modeling capability to provide reliable information about moisture in desert soils and ecologic condition.

8.0 References

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